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INESCTEC

SCIENCE & SOCIETY

BEYOND 5G COMMUNICATIONS

ABOUT US

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INSTITUTE FOR SYSTEMS AND COMPUTER ENGINEERING,
TECHNOLOGY AND SCIENCE
Campus da FEUP
Rua Dr Roberto Frias
4200-465 Porto
Portugal
+351 222094000
info@inesctec.pt
www.inesctec.pt

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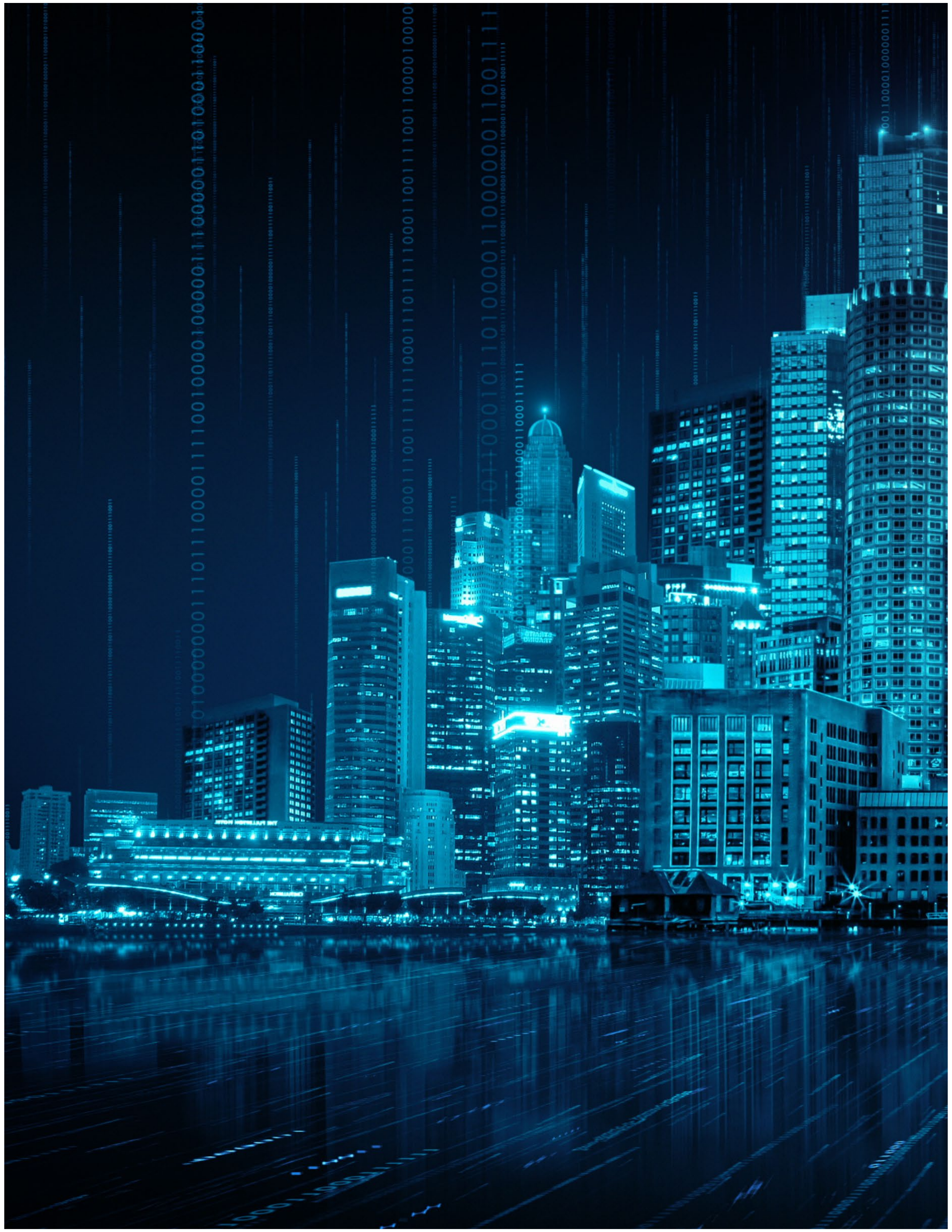
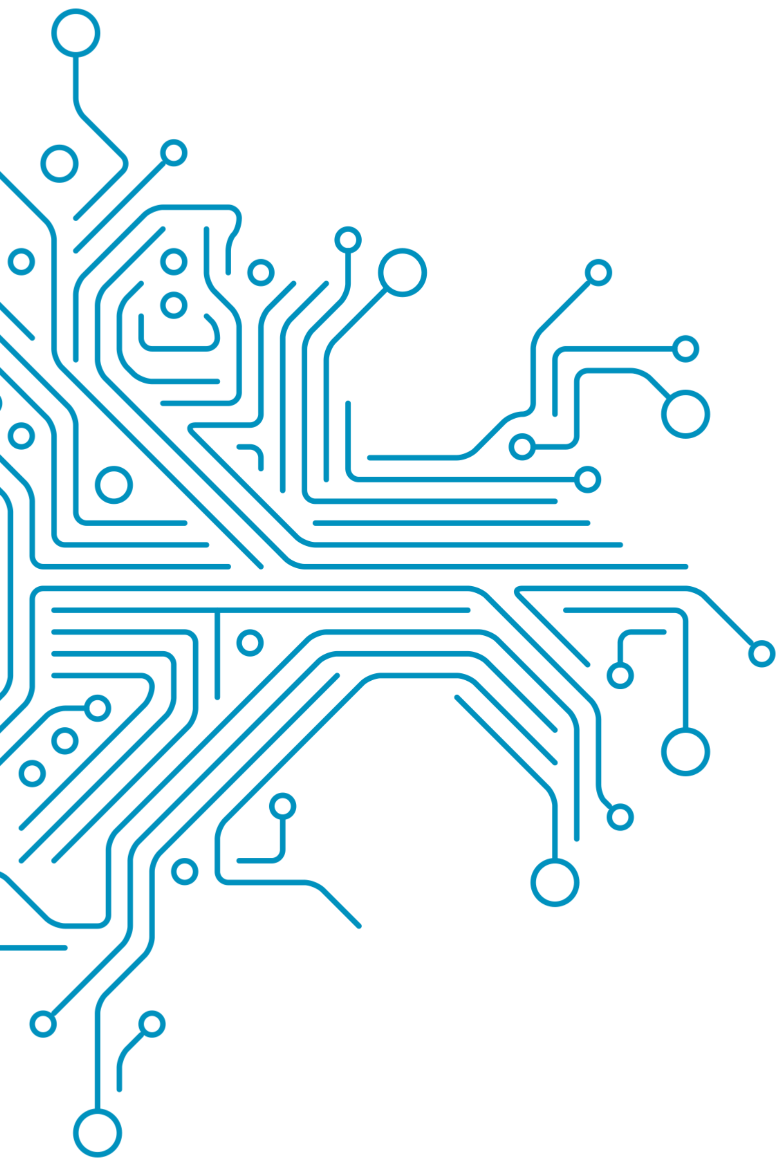
DESIGN
Camila Aldrighi (Communication Service, INESC TEC)

TRANSLATION
Francisco Azevedo (Communication Service, INESC TEC)

TECHNICAL SUPPORT
João Aguiar (Management Support Service, INESC TEC)





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1 OPENING

SCIENCE & SOCIETY

This is the third issue of the "INESC TEC Science & Society" magazine, created with the aim of disseminating science to society and contributing to the debate on emerging issues. It targets the general audience, hoping that it may be of particular interest to managers, politicians and technicians of the systems in which the themes dealt with are applied.

The magazine is distributed online every six months, covering a special theme in each issue, without excluding other articles on current issues. The autumn issue will always be dedicated to the same theme as the Autumn Forum, held by INESC TEC since 2015 – except for last year's edition, which unfortunately had to be postponed for a year due to the evolution of the pandemic, which created a delay that we hope to recover only next year.

It was with great satisfaction that we verified the excellent acceptance of the first numbers, the first dedicated to the health area, and the second focused on industry.

This edition addresses the topical theme of 5G. The authors are INESC TEC researchers and external personalities we've invited to ensure a more comprehensive outlook on the topic.

In addition to articles dedicated to the special topic, we also include articles on current affairs, in the final section of the magazine. In this issue, and given the increasing electricity prices today, we invited our researchers to write an article that explains how the Iberian energy market works and how prices are set.

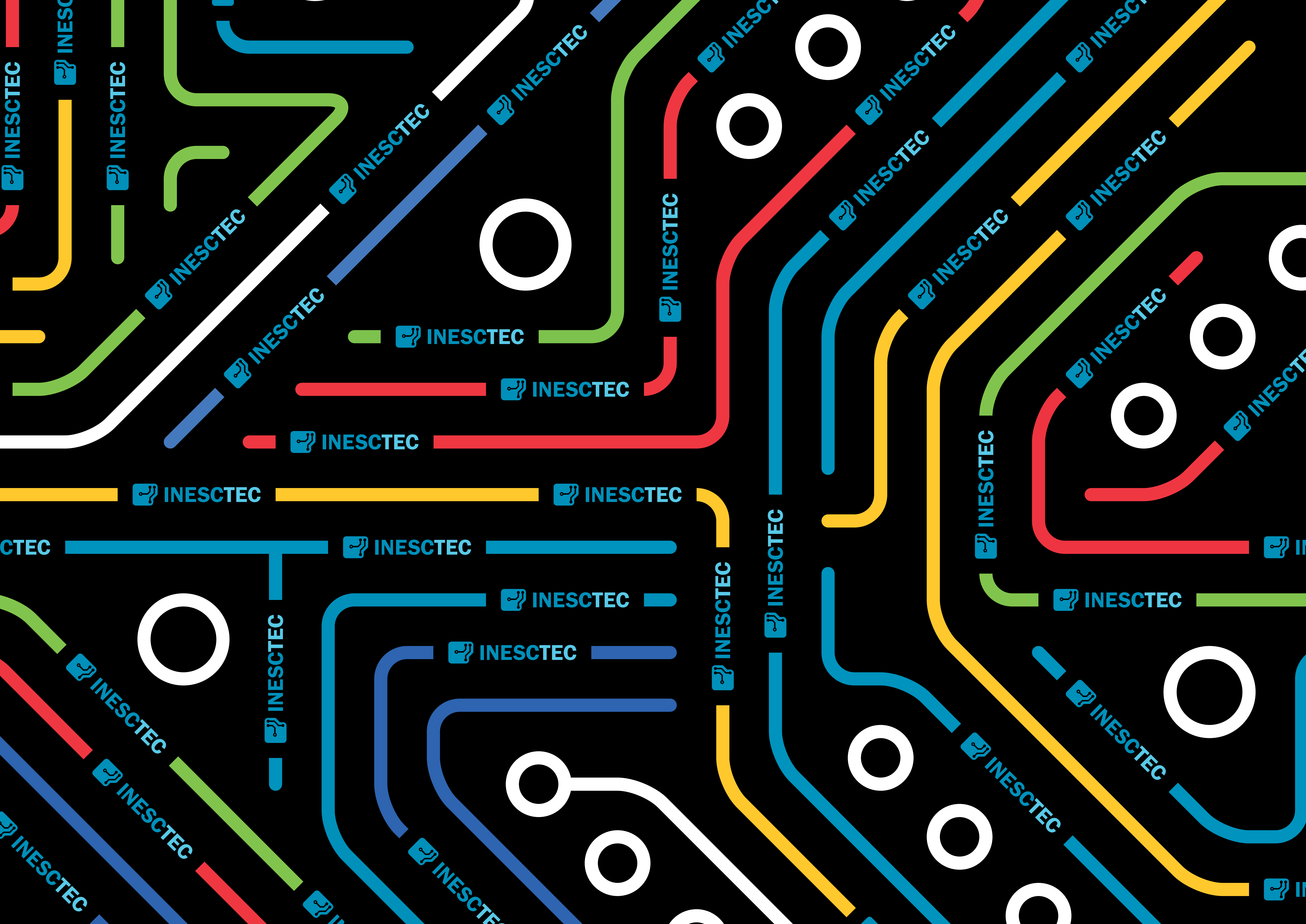
This article is a little longer than usual, as the topic is complex, but we have introduced it as a starting point for a future issue that we intend to dedicate to the topic of energy.

Moreover, we became aware of the visualisation constraints associated with the PDF, for viewers reading it on smartphones or even computers. Hence, we decided to change our dissemination model. In addition to the PDF format, all articles will be available online via HTML. The magazine's website also went through several changes.

I'd like to thank all those who contributed, highlighting the work carried out by the Editorial Board and INESC TEC's Communication Service, and, in particular, to the team of three editors of the Special Theme and all the authors.

We sincerely hope that the result is to your liking.

ARTUR PIMENTA ALVES [1,2,3]
(1) SERIES COORDINATOR
(2) PROFESSOR EMERITUS AT FEUP
(3) ASSOCIATE DIRECTOR OF INESC TEC
artur.p.alves@inesctec.pt


INESCTEC

2 EDITORIAL

The theme selected for this issue – **Beyond 5G Communications** – is timely, relevant to society and crucial to Portugal. Timely, because it matches the closing of the 5G auction in Portugal, the beginning of the installation of 5G by telecommunications operators, and the first tests of low-latency communications using 5G. Relevant to society, because the fulfilment of visions in sectors such as industry, healthcare, agriculture, smart cities, autonomous vehicles, and the sea fundamentally depends on ubiquitous wireless communications networks. Crucial to Portugal, because telecommunications are one of the main pillars for the implementation of the Recovery and Resilience Plan (RRP) and the Portugal 2030 programme, both focused on the digital transition and the energy transition.

Mobile communications have evolved remarkably over recent decades. 2G brought the first digital mobile voice service. 3G made the mobile broadband data service available for the first time, while 4G democratised mobile Internet access, anywhere and anytime. This path will continue with 5G, which will support new high-bandwidth services with low-latency requirements, including augmented reality, remote surgeries, and industrial Internet, with a scope that goes beyond the consumer market – Business-to-Consumer (B2C) –, the focus of previous generations. In the future, 6G will make it possible to create the real-digital continuum and connect digital brains, massively using sensors and artificial intelligence, and allowing natural communication between people and machines.

The articles presented in this issue discuss current and future mobile communications from various perspectives and dimensions. The first article, **ANACOM and 5G regulation**, addresses 5G regulation in Portugal, including coverage obligations by operators, infrastructure sharing, market dynamics, use of new spectrum bands and monitoring of 5G implementation.

In the second article, **Business model for 5G operators**, NOS describes its business model for 5G by characterising the potential impact on the industry value chain in sectors like the access network, platforms, systems, supply, sale, and services.

The third article, **Mobilisation of the national industry for 5G**, presents the Portuguese mobilising project 5Go, which involved a relevant group of national partners, including companies and R&D entities, and developed components for the access and core networks, as well as services for human and machine-centred communications.

The fourth article, **5G Communications in the Energy Sector**, addresses the needs of the energy sector and the potential of 5G technology in this application domain, pointing out relevant use cases including smart metering, electrical phasor measurement, and critical infrastructures' surveillance.

The fifth article, **Industry and 5G**, analyses the relationship between industry and communications, stating that the four smart industry maturity levels (visibility, transparency, predictability and adaptability) depend on the availability of wireless communications networks that will leverage new classes of applications and make industry and communications inseparable.

The sixth article, **5G in smart cities**, shows how 5G can be used to monitor infrastructures, water supply systems or even the implementation of public policies, as well as in the management of different urban traffic scenarios, to support the remote maintenance of infrastructures and the creation of new entertainment models.

The seventh article, **5G and Health**, addresses the issue of electromagnetic radiation caused by 5G. The article analyses the issue and focuses on antennas, densification of base stations and the use of high frequencies, concluding that there is no evidence of risks to human health stemming from exposure to radiation associated with 5G networks.

The following articles discuss the future of mobile communications. The eighth article, THz wireless communications: challenges and paradigm shift, explores the evolution of mobile communications towards the Terahertz communications band (between 100 GHz and 10 THz). In addition, it addresses the technological challenges ahead, including the high level of signal loss, the need for new electronics for these frequencies, the directionality of connections, the difficulty of signal processing in very wide spectrum bands, and the need for nano devices.

The ninth article, **Drones in 5G communications**, shows us another paradigm of the communications network, in which the network itself becomes mobile and airborne to increase traffic switching capacity and quality of service in geographic areas or for well-defined periods of time, in

firefighting situations or in cases with many people together in the streets, e.g., São João festivities.

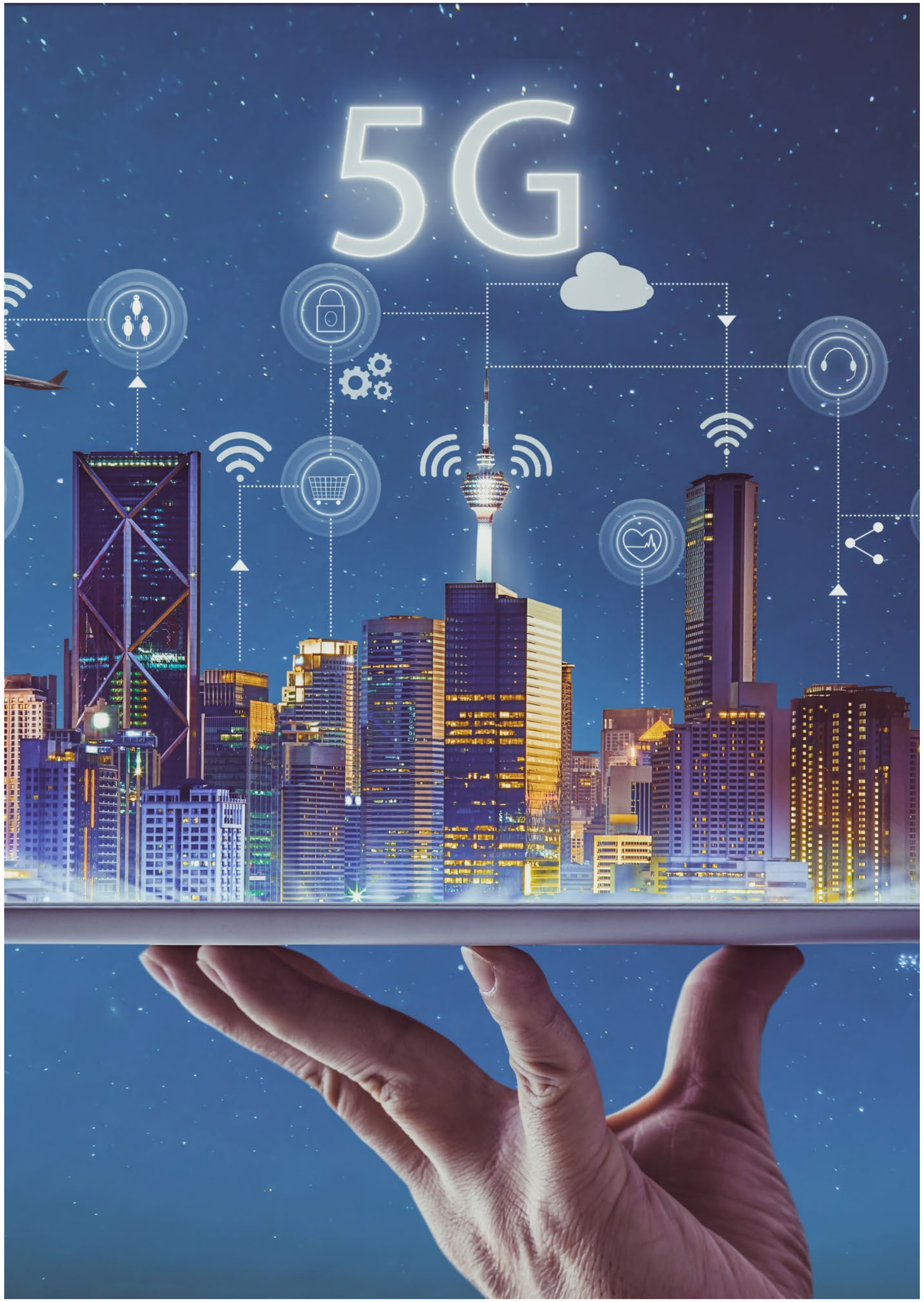
The tenth article, **Artificial intelligence – the Announced Revolution in Communications**, shows how artificial intelligence is changing communications and the paradigm of communicating. Relevant to this paradigm is the concept of federated learning, which focuses on learning in nodes and equipment located on the network edge, which learn cooperatively using collective intelligence techniques. These solutions will be important to the management and control of the telecommunications network, among others.

Finally, article eleven, **The Road to 6G**, provides us a unified and systematised view of 6G and the way to get there. This article also focuses on the potential applications and research areas, but also on the relevance of the experience gained in using 5G in the various application domains.

The next generation of mobile communications will be substantially different from previous generations. 6G will provide us a system that combines communications, sensing and computing in the same infrastructure. Its development will require advanced communications techniques and sensors, service-oriented software architectures, autonomous systems to support telecommunications equipment, ubiquitous artificial intelligence, edge computing, industrial processes dedicated to creating virtual networks on demand, and wireless power supply techniques to mobile and remote equipment. Therefore, the telecommunications of the future require a multidisciplinary development environment that must be prepared from now on.

INESC TEC presents itself as a relevant institution in this area. In addition to its multidisciplinary nature, stemming from the activities of its 13 research centres – which include the aforementioned fields –, it develops specific activities in the field of communication technologies and networks, electronics, multimedia and computer vision. These activities have been applied in multiple sectors of the economy, including telecommunications, industry, energy, media, mobility, healthcare, and space. Over the past five years, this activity led to more than 220 scientific papers, 10 patents granted, more than 70 research projects with industrial agents and partnerships with more than 40 entities.

MANUEL RICARDO [1,2]
RUI CAMPOS [1,2]
LUÍS PESSOA [1,2]
[1] INESC TEC
[2] FACULTY OF ENGINEERING OF THE UNIVERSITY OF PORTO
manuel.ricardo@inesctec.pt
rui.l.campos@inesctec.pt
luis.m.pessoa@inesctec.pt



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- Time sensitive networks
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- Multimedia services
- Multimedia communications
- Multimedia content adaptation
- Sound computing
- Machine learning for communications

STATISTICS (2016-2020)

220+ PUBLICATIONS

10 PATENTS GRANTED

70 PROJECTS WITH INDUSTRIAL CUSTOMERS

3 SOFTWARE REGISTRATION

41 PRIVATE PARTNERS AND PUBLIC FUNDING ENTITIES

5M€ INCOME

APPLICATION AREAS

TELCO	MEDIA	INDUSTRY	FOREST AND WOOD
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INFRASTRUCTURES

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Infographics developed by Filipe Ribeiro, Rui Campos, Luís Pessoa e Manuel Ricardo.

3 SPECIAL THEMES

BEYOND 5G COMMUNICATIONS

ANACOM AND 5G REGULATION

Since the arrival of mobile networks in the 1980s, new mobile generations have emerged every 10 years; the current decade is characterised by 5G, as shown in Figure 1.

JOÃO CADETE DE MATOS
PRESIDENT OF THE BOARD OF DIRECTORS OF
AUTORIDADE NACIONAL DE COMUNICAÇÕES (ANACOM)
jcmatos@anacom.pt

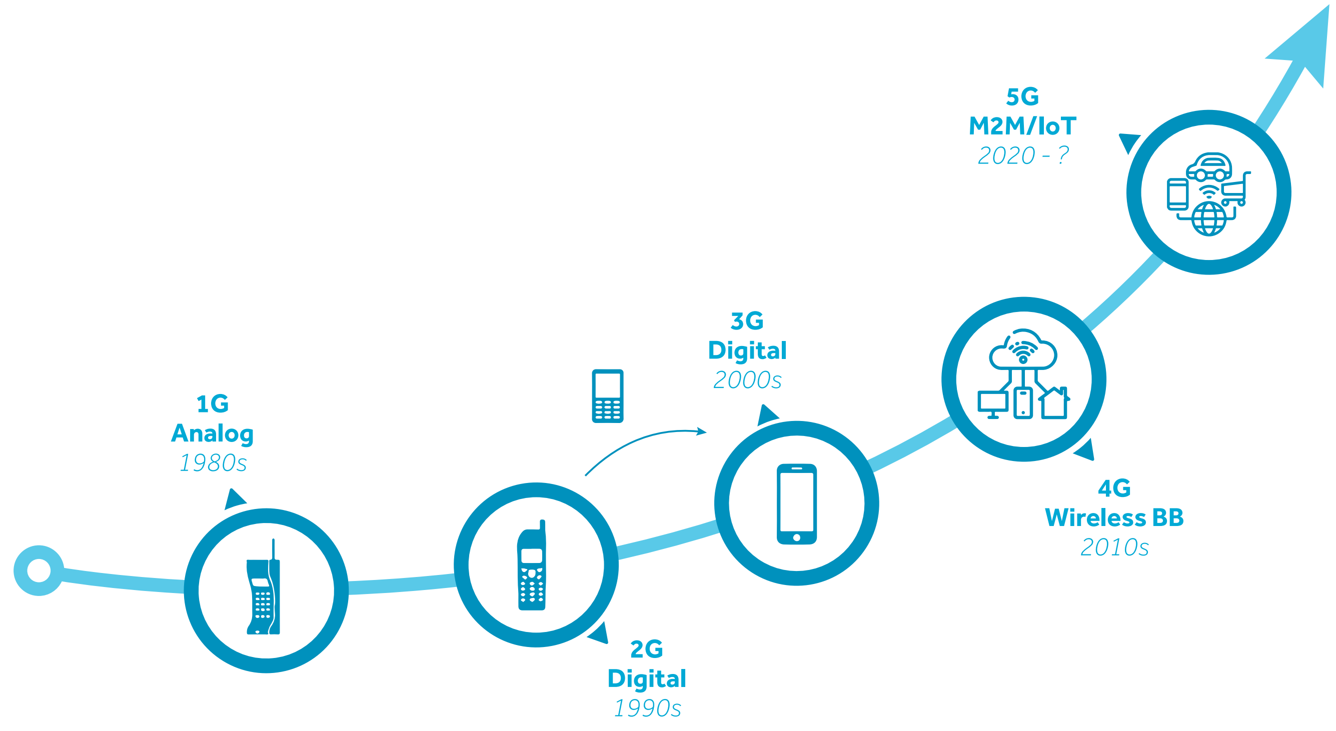


Figure 1 - Evolution of mobile generations | Adapted por INESC TEC.

However, 5G is more than a simple incremental evolution over previous generations. The first noticeable feature will be the increase in data transmission speeds. 5G will be much faster than previous generations, while low latency and high reliability will allow real-time interaction and mass machine-to-machine communications, as well as the implementation of multiple virtual networks over a single physical network infrastructure and the virtualisation of network functions.

5G will play a disruptive role in the market, due to the possibility of implementing and developing specific applications, enabling a wide range of applications in different sectors, e.g., education, healthcare, agriculture, industry and automotive.

The auction to allocate Rights of Use of Frequencies in the 700 MHz, 900 MHz, 1800 MHz, 2.1 GHz, 2.6 GHz, and 3.6 GHz bands in Portugal, which is currently ongoing, will lead to the allocation of Rights of Use in the 5G harmonised bands, as well as other bands.

Spectrum will be made available with different characteristics: lower bands (in the case of 700 MHz) will allow greater geographic coverage per antenna, but lower data speeds; higher bands (particularly 3.6 GHz) will favour increased capacity and higher data speeds, but with reduced geographic coverage per antenna.

The auction's main objectives are: (i) to promote social and territorial cohesion; (ii) promote greater competition in the electronic communications market and, consequently, help end-users derive maximum benefit in terms of choice, price, and quality of service; (iii) encourage effective and efficient use of the spectrum and (iv) pursue national and community goals in the field of digital transformation.

The auction also sets out conditions to increase and improve the coverage of national mobile networks, favouring less densely populated areas, and conditions which ensure that less economically attractive areas can also take advantage of 5G. As such, operators that acquire spectrum in the auction will be made subject to different obligations in terms of coverage, network development and improvement of the voice service signal.

One of the goals is to ensure coverage of 90% of the population in parishes with lower population density by the end of 2025, as well as the population of parishes in the Autonomous Regions of Madeira and the Azores, with mobile broadband at a minimum speed of 100 Mbps.

Priority coverage obligations are also defined in the provision of 5G-compatible services to hospitals, healthcare centres, universities and polytechnic institutes, business and industrial parks, ports and airports and military institutions, without neglecting the development of 5G in all low-density municipalities; all these obligations can be fulfilled by operators using their own or shared stations or using third-party stations through wholesale offers.

The auction regulation includes the reservation of spectrum for new applicants and network access obligations for current mobile network operators, whether under agreements for mobile virtual operator services (MVNO) or under national roaming agreements. The goal is to reduce barriers to market entry, promote competitiveness and to encourage new operators - including those with differentiated business models - to stimulate market development. This facilitates the emergence of new services and deals at competitive prices, with clear benefits for end-users.

National roaming and infrastructure sharing, both options available to operators, are tools that could reduce network development costs and allow multiple operators to provide mobile services in locations that, given their lower economic attractiveness, did not benefit from band coverage.

At the end of the auction, ANACOM is required to monitor operator compliance with coverage obligations, as well as associated obligations in terms of network access.

ANACOM has released a range of information on 5G, having conducted a series of webinars aimed at local authorities, leading to the 'Towards 5G Digital Guide'[1], with presentations and videos available to the public. And given significant public concerns about the impact of 5G radiation, ANACOM has published the results of electromagnetic field measurements, conducted following the various authorisations issued since 2017 to carry out 5G technical trials[2]. Elaborou também o guia "Redes Móveis e Saúde – factos, dados e desafios"[3].

ANACOM has also produced the guide "Mobile networks and health - facts, data and challenges", addressing false news and providing accurate information. This information is available on the 5G website, provided by ANACOM to answer the concerns and queries of the general public about 5G.

ANACOM will carry out a public consultation on the availability of the 26 GHz band, which will be an opportunity to assess, among other aspects, the spectrum needs of private networks using 5G. This frequency band will allow the development of hotspots with ultra-fast speeds, but with smaller geographic range compared to the lower bands.

The technical conditions governing the use of spectrum supporting 5G at 40 GHz are still being defined, while, in the case of 60 GHz, the National Table of Frequency Allocations (NTFA) already identifies the conditions of spectrum use, exempt from radio licensing, which also enable its implementation.

Some of the current mobile network frequencies may also be used by 5G (e.g., 1800 MHz, with tests already underway).

It will also be necessary to increase numbering resources to accommodate the foreseeable mass expansion of M2M/IoT devices and to keep up with the market's development, in order to promote competitiveness, mitigate potential barriers to entry and prevent new monopolies from emerging.

ANACOM will also play an active role in the implementation of the Connectivity and 5G Toolbox, which includes 39 best practices to reduce the installation costs of very high-capacity networks and to provide access to spectrum for 5G, with a view to promoting and speeding up the installation of these networks in line with the goals of the EU Gigabit Society.

We are certain that the introduction of 5G in Portugal will help drive digital transformation across all sectors of activity while, simultaneously, contributing to the country's economic, social, and territorial cohesion, meeting the legitimate wishes of the population and of the national economic fabric.

[1] https://www.anacom.pt/render.jsp?contentId=1631621

[2] MANUFUTURE Vision 2030, http://www.manufuture.org/wp-content/uploads/Manufuture-Vision-2030_DIGITAL.pdf

[3] https://www.anacom.pt/render.jsp?contentId=1540941

[4] https://www.anacom.pt/render.jsp?categoryId=345109

BUSINESS MODEL FOR 5G OPERATORS

The 5G is no longer a mere "G". It is a revolution! The combination of speed, latency, resiliency, and density it delivers creates the adequate conditions for immersive video, real-time video analytics, industrial and mobility systems intelligence, automation and robotisation, among many other changes.

MANUEL RAMALHO EANES
EXECUTIVE BOARD MEMBER, NOS
manuel.eanes@nos.pt

It is a productivity revolution with a very important economic impact, estimated at 1.300 billion euros globally, and 35 billion euros in terms of national GDP by 2035, according to the Roland Berger study "Harmonious development of the digital society in Portugal: the right 5G auction structure is critical". It cuts across the different sectors of economy and society, with an equally relevant environmental impact. According to the Ericsson study "ICT's potential to reduce greenhouse gas emissions in 2030", it is estimated that 5G will contribute to a 15% reduction in global emissions by 2030, while increasing productivity in agriculture up to 25%, and up to 20%-30% in industry.

As to the telecommunications sector, 5G is also a revolution in terms of technology, operational model, and supply. The impact is resonant and transversal, necessarily accelerating digital and environmental transition.

Step by step, let us take a closer look at the impact on the industry value chain.

Regarding **the access network**, there is, from the outset, an initial coverage effort that becomes increasingly important as traffic and the number of connected objects increases. Therefore, the challenges in terms of proper configuration and, above all, of optimisation, which is a permanent endeavour, are critical.

Impacts of 5G on the telecom industry value chain

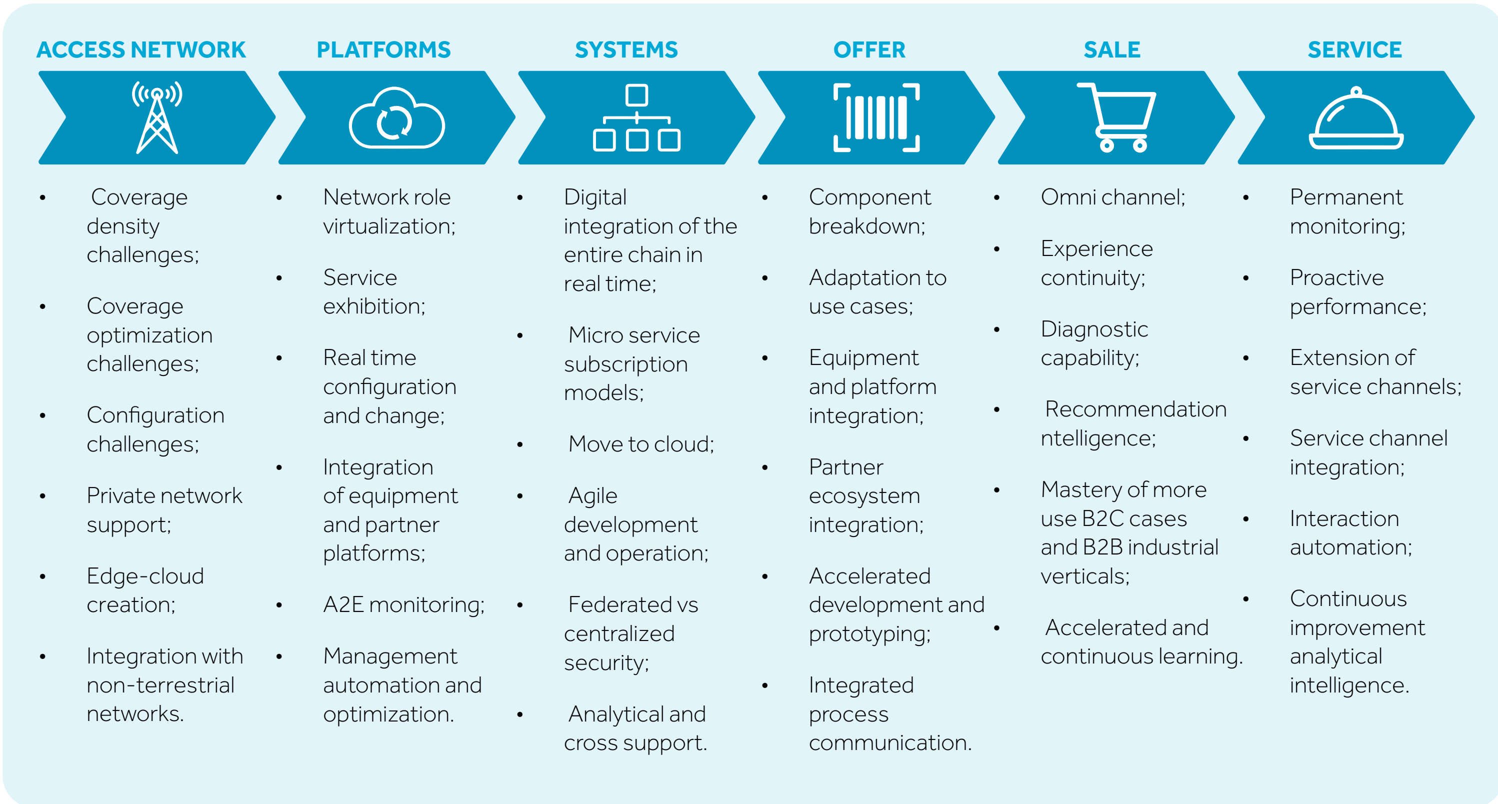


Figure 1 - Original from NOS SGPS. Adapted by INESC TEC.

5G requires more intelligence in the way the network interacts with each object, in order to enable a differentiation on how it addresses different needs. This makes the network even more "alive" and demanding in terms of design and maintenance. Hence, realising the full potential of 5G requires a novel network planning approach, namely: the public component will evolve to deliver greater performance and resilience in a context of rapid evolution of standards; the implementation of private networks for specific uses, e.g., industrial or healthcare, ought to comply with specific requirements, maintaining interoperability with the rest of the ecosystem; the non-terrestrial networks that ensure continuity and universal coverage - standard available from 2025 - will become crucial elements to coverage; and the creation of edge-clouds with computing and local hosting, critical to ensuring 1ms latency for critical applications like autonomous driving, will become part of access.

Alongside said effort, the virtualisation of **network functions** and the exposure of services are taking place at the platform level, enabling their real-time configuration and modification. The greater plasticity of the 5G when compared to previous generations is one of the most differentiating elements, due to its ability to adapt to the needs of each customer. Given that an "explosion" of equipment and solutions is expected, it is critical to be able to safely, but quickly, integrate this portfolio dynamic. The inclusion of all this potential and added complexity into monitoring systems is also vital. Likewise, we will have to optimise much of the current management and continuous improvement, since, even if desirable, it would be impossible to scale up the necessary skills.

Concerning **systems**, 5G creates the need but also the opportunity to accelerate the entire digitisation process. In order to subscribe services straightaway, as soon as one wishes to use them, a lot must change across the classic supply chain. The entire chain must adjust to a "real-time" mode: from user decision to network service. This implies the challenge of harmonising subscription models for services that are as atomic as necessary, while preserving the integrity of the whole, without generating an increase of operational complexity.

This requires plasticity, elasticity and speed throughout the entire chain and a complete migration process to the cloud. It also implies very agile development and operation models with the possibility of making infra-daily deliveries. Finally, it comprehends a new security design philosophy, in which federation and intelligence replace the perimeter "walls", and a very powerful, intersecting, and available analytical support that enables fast learning and automation.

The **supply** also undergoes a revolution inherent to the new potential of the chain, and the customers' new demands, used to low-effort and high-satisfaction digital processes. For a better and faster adaptation to the needs of customers, it must disaggregate itself from the outset. This granularity that will support the adaptation to more demanding use cases, like playing instantly, with more bandwidth and less latency, or starting remote surgery at a precise moment. Likewise, a broader and less stable ecosystem of third-party platforms and equipment requires more agile and flexible connections. Finally, taking advantage of the full potential of 5G means having very fast development and prototyping models in which communication integrates with the same speed.

Sales processes are not isolated from this reality. They will comply with an omnichannel approach. The customers expect and demand continuity of experience across the various channels, as well as intelligence and effort savings in diagnosis and recommendation processes. All of this represents a large analytical endeavour, but also an equal or greater effort in terms of communication, training, and support for business channels. Channels will have to master more use cases and more responses. It will certainly be necessary to create an environment and a process for accelerated and continuous learning. Finally, and probably most importantly, particularly regarding corporate and institutional customers and their high potential use cases, there is a significant need for shared understanding and collaboration between the customers and their operator, which implies a new business approach that is much more advice-giving, as well as reinforced skills to understand the business challenge and turning it into a viable solution with value for both parties.

Finally, the **service** will also have to change radically to become more proactive, intelligent, and invisible, as required. We must constantly monitor all relevant parts of the chain. We must act proactively and extend action to all relevant channels, in order to take full advantage of additional features, such as video. Similarly to what happens during the sale, the customers expect the continuity of their experience and the operator's visibility of their own experience. The tendency to tolerate fewer questions that we should know how to answer will increase. The customer will focus on quick problem-solving, while accepting automatic interactions that are fast and satisfyingly intelligent. All of this implies strong learning and continuous improvement efforts.

As to the operator, 5G is a revolution in the entire value chain, which combines exponentially greater potential with the increasingly higher demand of digital customers. NOS is aware and preparing itself for this massive challenge, towards becoming the leader of the 5G era in Portugal.

MOBILISATION OF THE NATIONAL INDUSTRY FOR 5G

5G communication networks will provide differentiated services to various sectors of society (vertical ecosystems), meeting the multiple requirements launched by the ITU-T for the 5th generation of cellular communications. 5G will reach maturity in 2025 and become part of the public (operator networks) and private (dedicated networks) domains, while interconnecting several wired and wireless access networks.

FRANCISCO FONTES (3)
RUI AGUIAR (4,5)
RUI CAMPOS (1,2)
MANUEL RICARDO (1,2)
(1) INESC TEC
(2) FACULTY OF ENGINEERING OF THE UNIVERSITY OF PORTO
(3) ALTICE LABS
(4) UNIVERSITY OF AVEIRO
(5) TELECOMMUNICATIONS INSTITUTE
fontes@alticelabs.com
ruilaa@ua.pt
rui.l.campos@inesctec.pt
manuel.ricardo@inesctec.pt

The communications infrastructure used by 5G will be characterised by a strong programmability, using virtualisation technologies such as Software Defined Networking (SDN) and Network Function Virtualisation (NFV).

Now that the commercial operation of 5G is beginning, there is significant expectation and interest among the communications and digital sectors. Previous generations of mobile communications focused mainly on the consumer market – Business-to-Consumer (B2C), while 5G features make it directly applicable to other sectors (e.g., industry), replacing traditional technologies such as the Ethernet.

The 5Go project was a mobilising initiative launched in January 2018, at a moment when commercial 5G networks were not operational yet. The project is closely associated with the ongoing global innovation in the field of telecommunications and was launched on the ideal date to maximise the development capacity of the national industry in this field. The project involved the most dynamic national companies in advanced telecommunications products and services (Altice Labs, Nokia, EFACEC, Altran and Wavecom), supported by several SMEs (Ubiwhere, OneSource, ITCenter and PDMFC), universities and research institutes (INESC TEC, Institute of Telecommunications and University of Coimbra), and the platform TICE.PT, towards promoting the collective and complementary development of different products.

The project's strategic objectives were defined in 2016 during the 5G technology specification phase. The project was quite innovative at a global level since it promoted the development of technologies and services for the 5G network before its standardisation. The reason behind it was the need to keep the Portuguese industry's competitiveness and deep involvement in relevant communications technologies, in an increasingly global market facing a growing digitalisation. Together, the 5Go project partners aimed to improve their international competitiveness by entering the new ecosystem created by 5G networks, developing new systems, and exploring the advantages of the new technology. The improvement in competitiveness was achieved through the updating of telecommunications supplying, towards entering new telecommunications markets and strengthening current markets.

In addition to the economic goal, the 5Go project also focused on renewing the national capacity to get involved in advanced communications, which are increasingly becoming the backbone of society. By involving more than 140 professionals and training a large number of MSc and PhD scholars, the project also contributed to a relevant national core of competences in 5G technologies that will certainly be of great use to the country.

From a technological point of view, this led to the creation of services and products crucial to enter new markets, according to four main vectors:

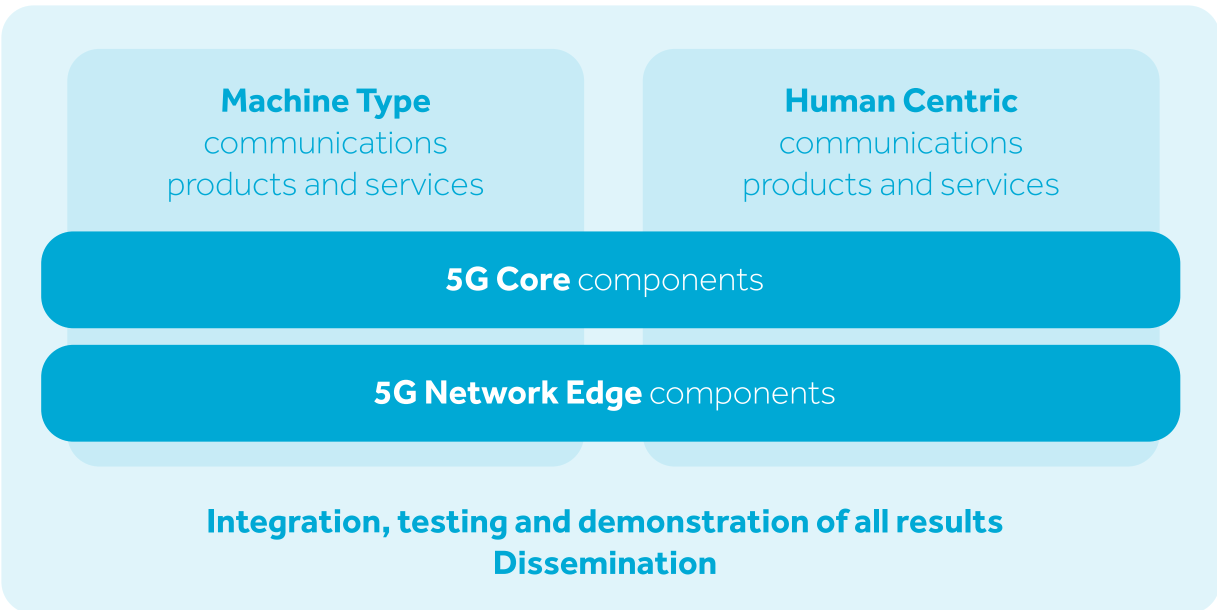
1. **A new line of products for the access networks,** covering the radio and optical network, including end-user devices, terminal devices for critical communication environments, and test units for operators, boosting companies' business volume and promoting new Business-to-Business (B2B) opportunities.

2. **5G network control components,** in terms of policies and external interfaces, as well as solutions for **managing new networks and services**, taking advantage of the different areas of 5G, including security, monitoring and quality of service, and advancing business niches for SMEs companies in the new 5G ecosystem.

3. Solutions for **video applications**, from personalised distribution to video surveillance, opening new markets for different companies;

4. Solutions for **critical environments**, enhancing the use of 5G technology in different vertical sectors, such as rail transportation and security solutions, strengthening the internationalisation capacity of these companies and allowing them to approach new markets.

Since this is a mobilising project, one of the main goals was the development of products that worked together. More specifically, the products developed for the access network are integrated with management, network control and security products. These products allow basic 5G technological support for vertical environments while enhancing the development and demonstration of 5G services and products in IoT fields (e.g., monitoring/control of distribution grids, railways, and vital signs), as well as products and 5G services for broadband multimedia transmission such as video distribution. The products developed throughout the 42 months of the project, according to these four vectors, cover all the functional domains of the 5G networks, reflected in the project structure, which followed the functional vision illustrated in the following figure: i) products for the access network, ii) products for the core network and iii) products for the vertical sectors. The latter are further organised into two other subprojects, one focused on machine-machine communication and the other on human communication.



Given the ultimate ambition of developing commercial products and the relative initial immaturity of the technologies under development, the project also contributed to the establishment of an environment that fostered the acquisition of knowledge about the competitiveness of different products. All products developed in the project were integrated, tested, and demonstrated in an ecosystem in line with the goals of 5G technology, benefiting from a realistic test environment. This environment, fostered at the Institute of Telecommunications in Aveiro, allowed to benefit from synergies with existing test environments and boosted technology tests at the level of TRL (Technology Readiness Level) 7 and 8.

The project results were widely disseminated, namely thanks to two seminars organised in October 2019 (in person) and June 2021 (online webinar, available on the project's YouTube channel). Readers can also check the results on the project's website (5Go.pt) and on the social networks Twitter, LinkedIn and Facebook.

5G COMMUNICATIONS IN THE ENERGY SECTOR

The modernization of the Energy sector has been witnessing fundamental changes, with the information and communication technologies (ICT) playing a key role. In the last decade distributed renewable energy resources have been paving the way for the highly needed decarbonisation of the sector.

DAVID RUA[1]
JOSÉ RUELA [1,2]
[1] INESC TEC
[2] RETIRED PROFESSOR FROM FACULTY OF ENGINEERING OF THE UNIVERSITY OF PORTO
david.e.rua@inesctec.pt
jose.ruela@inesctec.pt

Evolution of communications in electric grids

With it came the inclusion of advanced management and control schemes, which provide improved monitoring and automation capability to the energy grids and the ability to support new services and functionalities. The concept of smart grid goes one-step further, relying on intelligent schemes that run on ICT infrastructure capable of coping with different operational requirements and ensuring the necessary data exchange. On one hand, it is necessary to preserve the robustness of the electric grid characterised by high levels of reliability, availability and security and, on the other hand, it is possible to add the flexibility brought by adaptable and scalable mechanisms of energy resources to deal with the dynamic nature and growth of the grid.

The digitalization process has been initiated in the transmission and distribution side, where systems like SCADA have already been used for decades in substations, to monitor and manage assets through a growing number of connected devices and systems, such as remote terminal units (RTU) and intelligent electronic devices (IED). Smart meters have been deployed to monitor the demand consumption and more recently the generation, and to support the management of the grid. They also drive the digitalization of the distribution grid with monitoring and automation features installed in secondary substations, which act as intermediary nodes of a large and complex digital system. Adding to the puzzle is the generalization of distributed renewable generation and electric vehicles, with their highly desired dual roles: as flexible loads or as potential generators.

The heterogeneity of operational requirements in the different segments of the grid and the need to exchange more data to support advanced services and functionalities (e.g., grid monitoring, energy forecasting, predictive control, enhanced grid automation) is introducing new problems that require the exploitation of diverse ICT systems. The result so far is a plethora of technologies and solutions tailored to either general or specific needs [1]. Although the harmonization among electric grid segments has been supported by industry-led standards, notably from the IEC, it is still necessary to solve cross-segment specificities that have been raised with distributed management and control strategies. These were triggered almost 20 years ago by revolutionary concepts such as the microgrid, with several reinterpretations and currently reemphasized in concepts such as cloud, fog, and edge computing. Communication architectures have evolved into more complex formulations, creating yet another challenge in dealing with different needs of connectivity and data exchange for modern grid applications, as portrayed in Figure 1.

The Internet-of-things (IoT) is being used in smart grids to integrate more devices, flattening ICT architectures, whilst coping with edge and cloud concepts. Despite this and other architectural innovations, the underlying communication technologies struggle, on their own nature, to provide capable solutions for the different requirements.

The use of privately owned ICT infrastructures has been preferred due to historical reasons and specificities of the electric system, i.e., the need to keep it isolated from other systems. The option for telecom-based technologies like 4G has been reluctantly taken in cases where other technologies are either expensive or incapable of fulfilling the requirements. Telecom services for smart grid application have been a niche, as the core business of telecom operators is not entirely aligned with the needs of utilities. Cellular technologies still introduce limitations to the exploitation of flexible business models for grid applications with an impact on costs, particularly in cases where to support specific scenarios the compensation of lost revenue comes with a non-negligible price tag. This is an opportunity for 5G to contribute to the change of the current *status quo*.

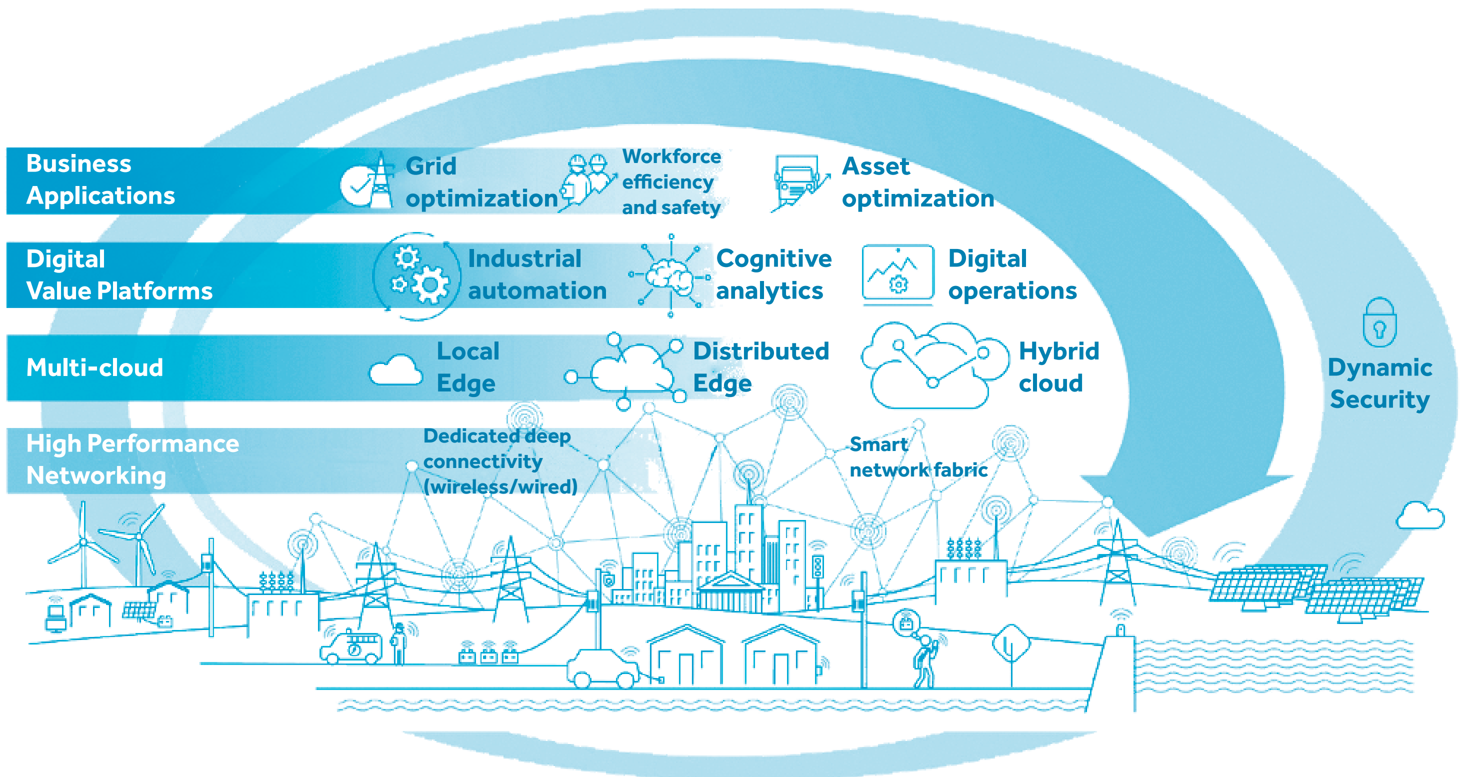


Figure 1 - Connectivity for smart grids. Original Nokia-Bell Labs (Labs Future X). Adapted by INESC TEC.

5G as enabler for the Energy sector

5G technologies are changing the game and assuming an important role in the Energy sector, as enablers of new services, applications, and business opportunities. Key concepts and architectural aspects [2] that distinguish 5G from earlier cellular technologies (including 4G, which 5G will progressively replace) make it suitable to support the most critical requirements of diverse technical and business use cases of the energy context.

5G New Radio technologies allow much higher data rates, with different channel sizes and flexible resource allocation modes tailored to the type of service to support; this does not preclude the use of other wireless access technologies (e.g., 4G), which may coexist during an interim period.

5G networks rely on software-based techniques, namely virtualisation of network functions (e.g., access and mobility management, authentication, policy control) that run on a general-purpose hardware platform, and on the adoption of the software-defined networking paradigm that allows dynamically reconfiguring and speeding up the packet forwarding process.

The organisation and operation of 5G networks is centred on the novel slice concept. As illustrated in Figure 2, network slicing is used to create and run multiple, self-contained logical networks on a common physical infrastructure. A slice is configured with network functions, applications and resources to meet the requirements of a specific use-case, coupled with a business purpose.

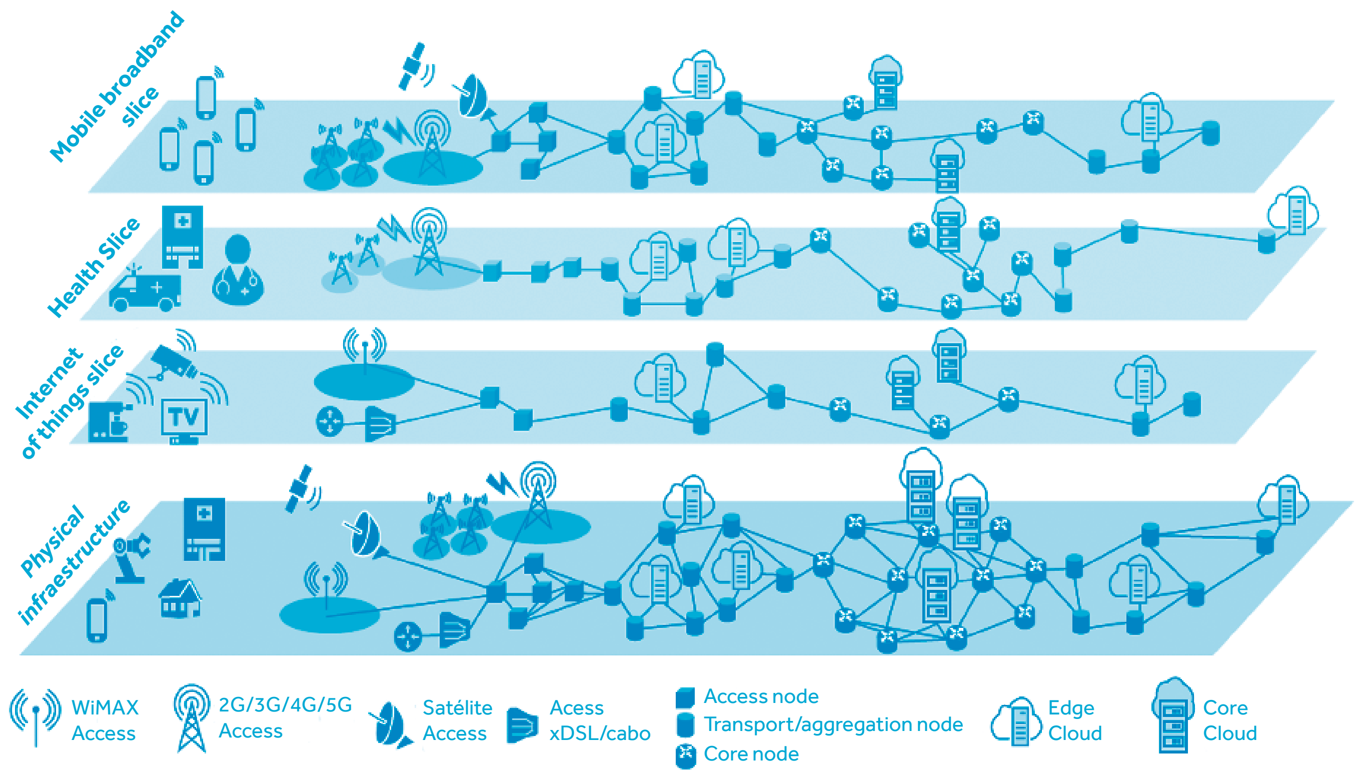


Figure 2 - Network Slicing for 5G with SDN/NFV: Concepts, Architectures, and Challenges. Original Jose Ordonez-Lucena, Pablo Ameigeiras, Diego Lopez, Juan J. Ramos-Munoz, Javier Lorca e Jesús Folgueira, "Network Slicing for 5G with SDN / NFV: Concepts, Architectures, and Challenges", IEEE Communications Magazine, maio de 2017, pp. 80-87. Adapted by INESC TEC.

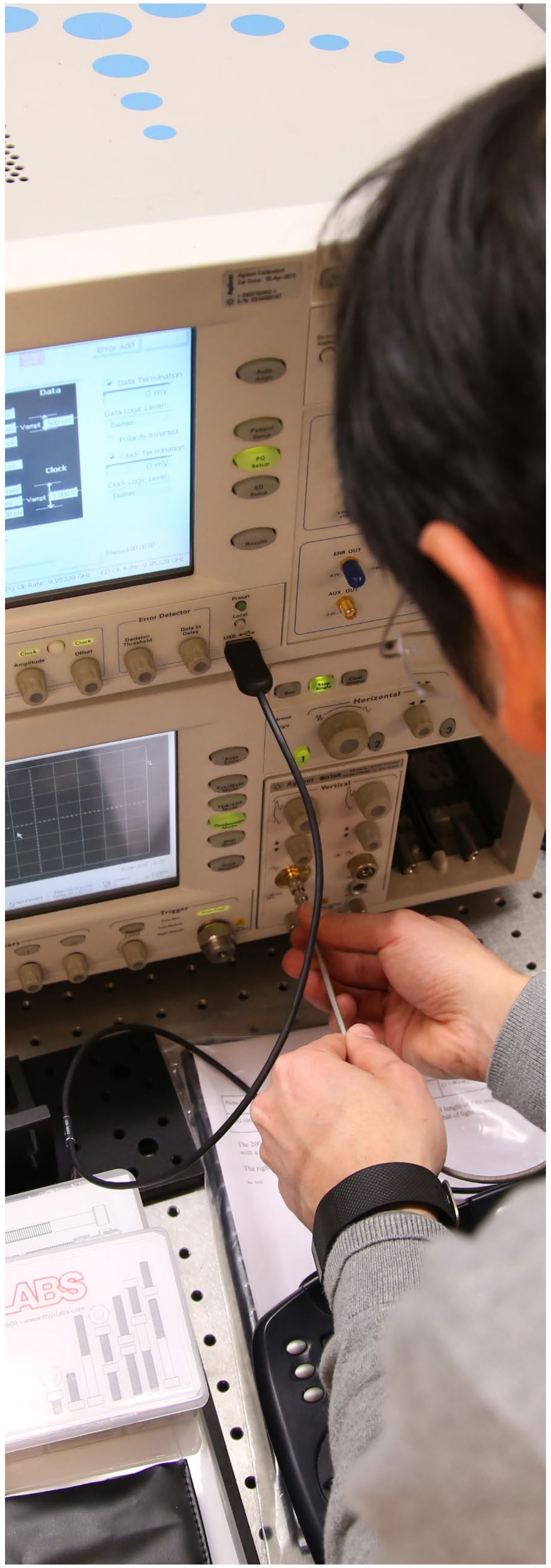
The role and importance of 5G in the Energy sector may be assessed now from different perspectives.

First, the 5G technology may be used in all segments of the electric grid and the 5G network architecture is easily integrated with the cloud computing model. A flexible and optimised development and deployment of smart grid applications is, thus, possible; for example, time-critical applications may run in edge systems, closer to the information sources, while computer intensive

Secondly, typical smart grid applications may be supported on standard slices already defined to address generic service categories with very different characteristics and requirements, but slice customization is possible too.

Smart metering is a case for using a massive Machine Type Communications (mMTC) slice, which is optimised to handle a large number of devices that generate low volumes of non-time-critical data. Coordination of microgrid automation systems may be mapped to an Ultra-Reliable and Low Latency Communications (URLLC) slice, which is targeted at applications that have stringent delay requirements and need very high reliability and availability. Video surveillance of critical infrastructures (e.g., primary substation) fits well into an enhanced Mobile Broadband (eMBB) slice, which is intended for (multimedia) applications that require high data rates. Using 5G drones in surveillance, planned maintenance activities or emergencies requires two types of slices: eMBB for video processing and analysis and URLLC for drone flight control.

Finally, the potential use of 5G in the Energy sector goes far beyond the current applications. As the technology becomes widely adopted and matures, more advanced use cases and business models will appear, benefiting from the assessment of experimental results and the expertise gained with the use cases of today.



[1] Y. Kabalci, "A survey on smart metering and smart grid communication", Renewable and Sustainable Energy Reviews, Volume 57, 2016.

[2] Alcardo Alex Barakabitze, Arslan Ahmad, Rashid Mijumbi, Andrew Hinesd, "Corte da rede 5G usando SDN e NFV: Um levantamento da taxonomia, arquiteturas e desafios futuros", Redes de Computadores, Volume 167, 11 de fevereiro de 2020, Artigo 106984.

INDUSTRY AND THE 5G

Industry in Europe, including Portugal, is quite relevant. It accounts for over 20% of the EU economy, directly employs around 35 million people and contributes to over 80% of exports, making it crucial to future progress and prosperity.

AMÉRICO AZEVEDO [1,2]
MANUEL RICARDO [1,2]
[1] INESC TEC
[2] FACULTY OF ENGINEERING OF THE UNIVERSITY OF PORTO
americo.azevedo@inesctec.pt
manuel.ricardo@inesctec.pt

Although European industry still has a competitive advantage on many high value-added products and services, it is under a significant transformation towards a greener and more digital industry to ensure its competitiveness.

It is undeniable that digital technologies can transform the face of the Industry and the way value is created, delivered and captured. Digitalisation fosters the emergence of new business models, enables Industry to be more efficient, provides workers with new skills and supports the decarbonisation of the economy, by providing a source of clean technological solutions and actively contributing to the European Green Pact.

The industry is in the midst of a historic moment of development. The challenge is to create companies with learning capabilities, agile and able to continuously adapting to changing conditions. The faster an organization adapts to an event that causes a change in its operating environment, the greater the benefits of adaptation. The aim is therefore, to drastically reduce the time between the occurrence of an event and the implementation of an appropriate response. This means that, for example, unexpected changes in the 'factory floor', captured, propagated and understood in due time, can be taken into account during the manufacturing process of a product, because the company guarantees the agility to adapt to the new situation.

Technologies around 5G are essential to ensure the competitiveness of tomorrow's industry . They are essential because they enable the implementation of adaptive y strategies – the natural ambition of smart businesses.

Therefore, with the rise of 5G, batteries are pointed towards the development and implementation of so-called smart factories – data-centric, with reduced latency, unpredictability, and with high levels of interoperability. This evolution towards a smart industry implies embracing four key maturity stages, namely:

I. Visibility – What is happening?

II. Transparency – Why is it happening? To understand why something is happening and to use this understanding to produce knowledge through root cause analysis. In order to identify and interpret interactions, the captured data must be analysed through the application of engineering knowledge.

III. Predictability – What will happen? Once companies are able to anticipate future events, they must also be prepared to take the necessary steps to minimise the potential negative impacts of these events.

IV. Adaptability – autonomous and intelligent responsiveness; the result of the combination of advanced connectivity, processing power, and artificial intelligence located in the devices that use and generate data.

The smart industry maturity stages therefore depend on factors related to communication networks and their applications. The mobility of people and objects without communication restrictions is the first of these factors, and will enhance the emergence of new mobile equipment including intelligent forklifts or intelligent robots, sensors anywhere, tracking of objects and people, modular production lines, or new forms of human-machine interactions that, for example, allow an operator to wear augmented reality glasses.

Mobile computing and communications brought to every object and person, whether on the factory floor or in industrial processes and chains, on the other hand, potentiates a number of new applications that will combine local information with information available in the cloud. The ideal communications network, characterised by instantaneous transfer of large amounts of data anywhere and anytime, allows us to think of applications that include the Internet of the senses with the possibility of transferring smells and sensations, holographic communications, the real-digital continuum with the human entering the "computer game" or their real environment being reconfigured, humanoid robots communicating with each other or with people.

Unlike mobile communications from previous generations, 5G will allow us to create multiple wireless networks, coexisting in time and space, each dedicated to the transporting of data from applications with specific characteristics. This ability to adapt and reconfigure 5G allows us to create wireless networks offering 1 Gbit/s to a terminal, or information transfer delays of less than 10 ms, or the possibility of obtaining information from equipment located in areas with difficult radio access.

5G also differs from other wireless communication technologies, such as Wi-Fi, in the reliability associated with it. Unlike Wi-Fi, which transmits on open -access radio channels and is therefore subject to interference, 5G works on exclusive-access radio channels – without interference. On the other hand, 5G does not have the low transmission power limits of Wi-Fi that require the installation of a large number of radio access points, so the 5G radio infrastructure of a factory is simplified.

A relevant aspect for the industry is the use of 5G private networks. Countries such as Germany or France allow a company to broadcast radio exclusively within its premises, without interference from third parties, allowing it to create its private 5G network. Various models of private networks can be adopted, some of which would be in partnership with telecom operators. This versatility of 5G is very relevant because it will allow each company to move forward in defining using 5G communications networks at its own pace and considering its communications needs.

Industry and 5G will be inseparable partners in the times ahead.

5G IN SMART CITIES

Digital technologies for smart cities will, among many other aspects, facilitate the changes needed to increase sustainability and foster the adaptation to climate change. The evolution of mobile networks - in the short term with 5G - brings as main novelty the provision of differentiated services for communication between equipment (devices and services) and people.

ANA AGUIAR [2,3]
PAULO PORTUGAL [1,2]
[1] INESC TEC
[2] FACULTY OF ENGINEERING OF THE UNIVERSITY OF PORTO
[3] INSTITUTO DE TELECOMUNICAÇÕES
ana.aguiar@fe.up.pt
pportugal@fe.up.pt

This is reflected in a greater capacity to interconnect huge amounts of devices per square meter (the massive Machine Type Communications - mMTC service), the possibility of having high reliability and very low latency in some communications (the Ultra Reliable Low Latency Communications - URLLC service), and the ability to provide high throughput for specific applications (the enhanced Mobile Broadband - eMBB service). These services will be provided not only through the installation of new infrastructures for the various frequency bands of the access networks (700MHz, 3.5GHz, 26GHz), but also via the integration and evolution of existing technologies (including 3G/4G and NB- IoT, WiFi, etc.). Although the use of new frequencies has raised concern about the risks to people and animals' health, there is no scientific evidence to support it so far, as detailed in a recent study by the EC Joint Research Center [1].

These three types of service will be supported by different physical access techniques, and by the separation of traffic flows at the network level. This separation is known as slicing, and it is made possible through a technology called software defined networking (SDN), which changes the paradigm of network traffic forwarding. Instead of decentralised algorithms, which take more time to reorganise routes and treat all data packets equally, we move to a centralised paradigm. A controller has information about all nodes, connections and flows, and can change flow pathways in a centralised way with fine granularity. This evolution may come to contradict the principles of network neutrality, if due care is not taken in the provision of sufficient additional resources to support the new, more demanding services (namely the URLLC), while preserving the quality of other services.
There will also be fundamental changes in the organisation of services that build the core of the network. Core services will become virtualised, leveraging Network Function Virtualization (NFV) technology. They will no longer be strongly integrated with the equipment where they are executed, thus enabling an organisation of the core functionalities as micro-services running on generic equipment.

From an economic point of view, the possibility of using generic equipment and software modules from different suppliers is expected to create many opportunities for innovation in network components. A great effort is being invested towards the development of open-source software components, mainly under O-RAN, with many operators involved. This will push innovation in network components.

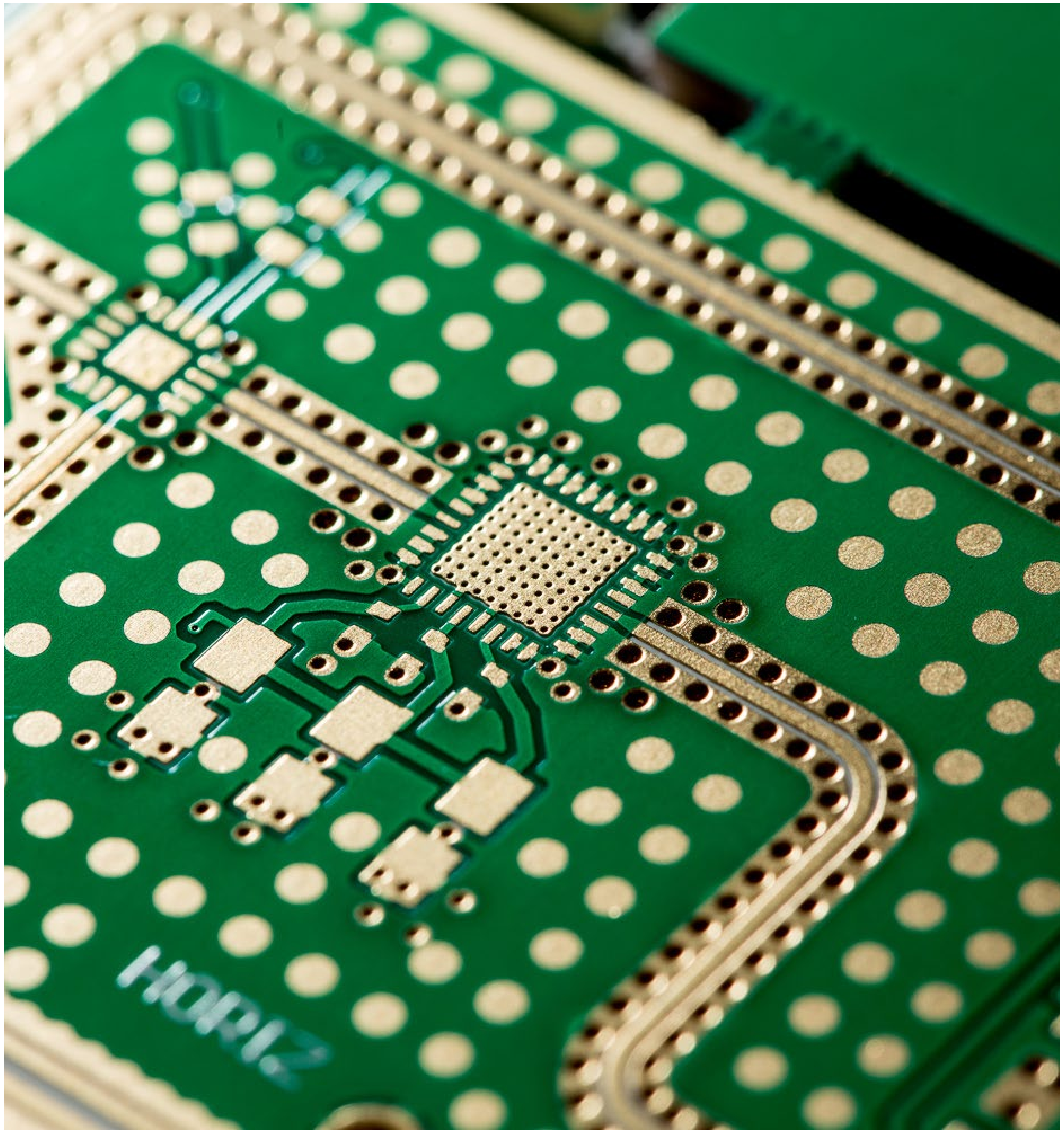
What does this mean for smart cities?

The greater sensing capacity will facilitate the collection of data with finer spatiotemporal granularity, allowing for greater knowledge about all the city's processes, both public and private. This includes the monitoring of infrastructures, natural resources, microclimates, rainwater, as well as following-up the implementation of public policies, etc. This data will also feed a digital twin of the city, which can be used to study the impact of public policies, events, or to predict anomalous occurrences and their consequences. This more accurate and granular information allied to greater actuation capacity, will also favour a more agile automated control of some of these processes, using the processing capacity of cloud computing. Examples of these scenarios range from managing mobility and air quality, the electric grid, local producer-consumer networks or the electric car charging network, to personalised warnings about health risks in cases of extreme weather events, since it will become possible to assess risk at both the individual and neighbourhood level. Greater knowledge about the city will also enable the adequate management of the network infrastructure itself, assessing where and when certain services will be needed. The time scales of these control applications range from several minutes to hours.

The high reliability and low latency URLLC service will allow other types of applications, for fine control of various processes in sub-second timescales. The easiest application to imagine is managing traffic scenarios with autonomous cars and all other users of public spaces, vulnerable road users. In these scenarios, the various mobile nodes (vehicles, pedestrians, cyclists, other new means of transportation) must communicate with each other within milliseconds, in order to exchange information collected by their multiple sensors, allowing a better understanding of each one's situation. In busy areas, where traffic situations are more complex, data processing is expected to not take place exclusively on the mobile nodes themselves, but rather be supported by more powerful computing resources available close to the network access (as opposed to the cloud, on the network's core). The usage of these computational resources with low latency can only be achieved by a very efficient and granular network management, enabled by slicing, SDN and NFV technologies.

Another relevant scenario is the use of augmented reality for various daily tasks, which will be supported by eMBB, eventually combined with others. The city's data flows and the possibility of precise location, combined with high-resolution multimedia content, allow highly innovative mixed reality experiences. An example is the maintenance of infrastructures and equipment supported by remote experts. Others are entertainment applications associated with leisure and tourism in public spaces, e.g., a game with virtual beings in the city space, a guided tour in a Star Wars environment accompanied by Jedi and Sik, or the participation in the liberal wars in Porto.

The openness and flexibility of the network and equipment along with the associated innovation will allow cities and communities to complement the coverage of the operators' networks more easily. This will make it easier to ensure the universal access to these new services at a faster pace.



We dare to say that one of the biggest challenges to the technical realisation of these scenarios is the security of all components and of the integrated system. The opening up of communication networks, the greater number of entry points into the network, and the use of open and interoperable components, increase the attack surface and make it more complex. The scientific and technology community are currently addressing these challenges, and we are confident that they will timely find adequate solutions.

5G is an integrative term for a broad set of innovative technologies that are expected to promote a high degree of openness and innovation, both in the network itself and in the applications that run on top of it. 6G is now starting to grow as a research area, focusing on the evolution towards increasingly integrated architectures for communications and computing networks, taking advantage of artificial intelligence to achieve greater efficiency, with a focus on scalability and energy. Communications and networks will continue to evolve to interconnect a dense and ubiquitous fabric of computing nodes that will support services increasingly focused on improving citizens' quality of life.

[1] https://publications.jrc.ec.europa.eu/repository/handle/JRC123365

[2] https://www.o-ran.org

5G AND HEALTH

Since 2017, several movements appeared worldwide disputing the introduction of the fifth generation of mobile communications systems (5G), claiming for a moratorium until it is clarified whether there are harmful effects for people's health and for the environment but there is no evidence to date that there is a health risk from exposure to radiation associated with 5G communications networks..

LUÍS PESSOA [1,2]
LUÍS M. CORREIA [3,4]
(1) INESC TEC
(2) FACULTY OF ENGINEERING OF THE UNIVERSITY OF PORTO
(3) INESC ID
(4) INSTITUTO SUPERIOR TÉCNICO - UNIVERSIDADE DE LISBOA
luis.m.pessoa@inesctec.pt
luis.m.correia@tecnico.ulisboa.pt

Some extremist anti-5G groups burned telecommunications towers in several countries, while others have developed theories of conspiracy associating (without any scientific support) 5G to COVID-19. In the meantime the World Health Organization (WHO) alerted the public to the false news[1] that were spreading through social networks, explaining that there is no link between 5G and COVID-19, and stressing in particular that the disease has also spread in countries that do not have yet such networks.

Social concerns in relation to 5G are similar to those that existed in the past with regard to previous generations (2G, 3G and 4G), in particular due to the fear that exposure to electromagnetic radiation has adverse health effects.

STUDIES

Many studies on the subject have been carried out within the last decades up to the present, namely epidemiological, in-vitro and with animals, evaluating various potential effects with regard to carcinogenicity and fertility, among other aspects. While several epidemiological studies have obtained mixed results, and therefore not showing any causal association between the use of mobile phones and cancer risk, some animal studies have shown some evidence of carcinogenic effects[2]. This situation may cause concern, but it should be recalled that a fundamental step in the scientific process is the need for repeatability, and the problem of these studies is precisely the lack of repeatability and consistency among them. In the recommendation of 2020[3], the International Commission for Non-Ionizing Radiation Protection (ICNIRP), formally recognized by the WHO, after analysing the most recent studies, considered that there was no consistent and reliable evidence because there are inconsistent results among studies and methodological failures, suggesting additional studies.

Despite the lack of consistent scientific evidence, the feeling of fear regarding 5G seems to have gained more strength than regarding previous generations of mobile communications, probably exacerbated by social networks. It is undeniable that nowadays it is much easier for a misinformed (or ill-intentioned) person to disseminate a partial or distorted analysis of the facts, creating apparently alarmist conclusions for the common citizen.

The question then arises: what is different in 5G compared to previous generations and what argue those who criticize it?

5G can be distinguished from previous generations in many points, but here we focus on the three main aspects that have been pointed by anti-5G movements:

ANTENNAS

5G critics argue that the use of active antenna technologies known in the technical field as MIMO (Multiple Input Multiple Output) and beamforming technologies will increase exposure to radiation, which is not correct. MIMO consists of the use of antenna arrays (i.e. planar antennas with several elements) in order to take advantage of multiple propagation paths and thus increase of data transmission speed, while beamforming consists of using these arrays to concentrate the transmitted power towards the user terminal. Although the power emitted by 5G base stations is similar to that transmitted by 4G stations, the use of active antennas leads to a dynamic variation of the antenna radiation lobes in time and space according to data traffic requirements and / or with the geographical position of users. This dynamic variation means that radiation is transmitted only in the directions of interest and only during the minimum necessary time, leading in practice to a lower average exposure of about 20 to 30% compared to 4G.

[1] https://www.who.int/emergencies/diseases/novel-coronavirus-2019/advice-for-public/myth-busters

[2] F. Belpoggi, "Health impact of 5G", STOA / Panel for the Future of Science and Technology. doi: 10.2861/657478

[3] https://www.icnirp.org/cms/upload/publications/ICNIRPrfgdl2020.pdf

DENSIFICATION OF BASE STATIONS

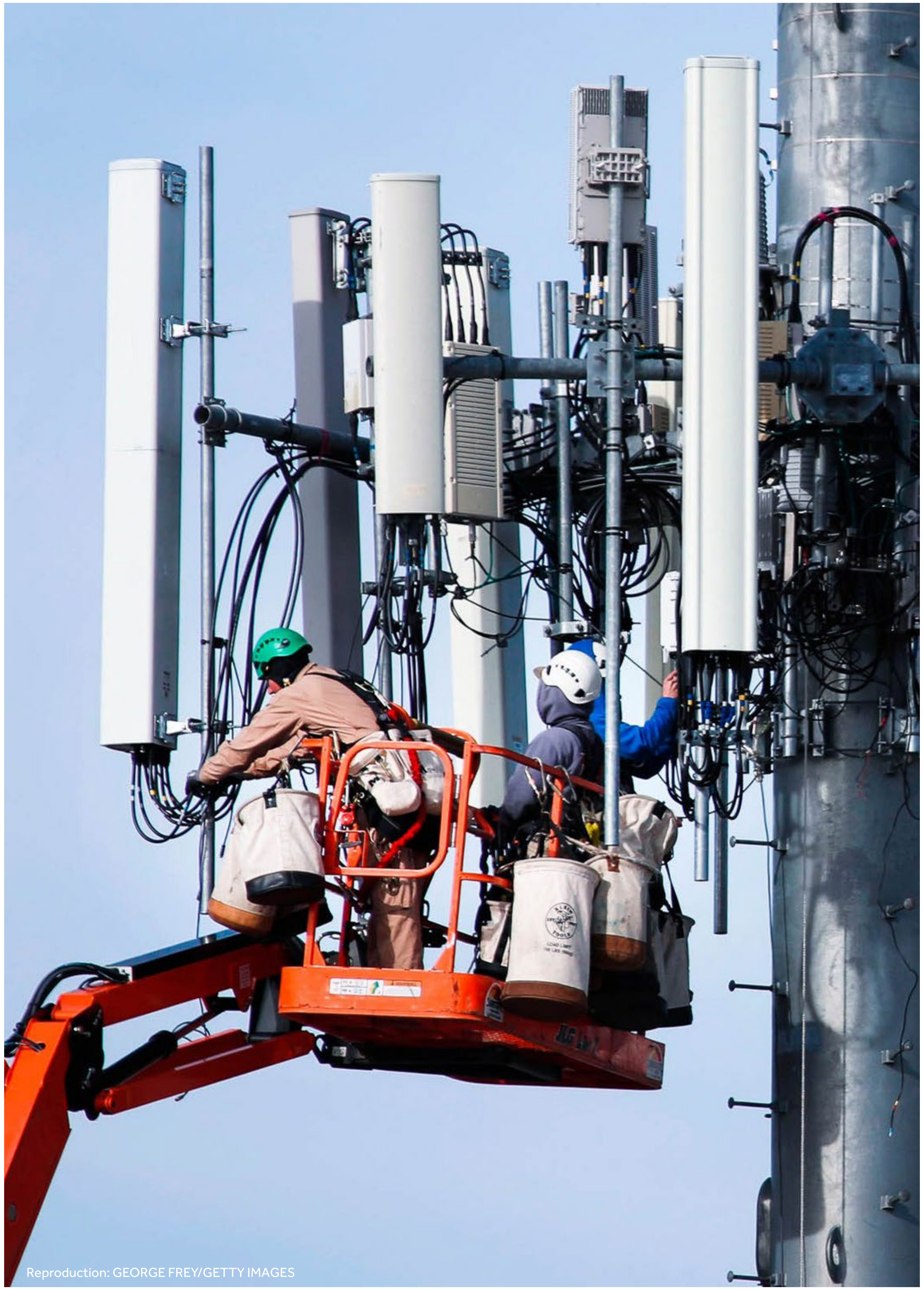
The densification of base stations is often mentioned by anti-5G groups, because at first glance it seems intuitive that this densification leads to an increase in exposure to radiation and as such to increased health risks. However, this is another example of a theory developed without correspondence to the reality. In fact, more base stations will be required in 5G due to the fact that some of the used frequency bands are higher than those used in previous generations (at 3.6 GHz in particular), in order to support higher bandwidth communications; as signals in these frequencies suffer higher attenuation with distance, it is necessary to deploy more base stations throughout the territory in order to maintain the same coverage for users. However, let us consider an analogy with street lighting lamps to realize that in a network with a large density of base stations (lamps), each station has to cover (illuminate) a smaller area, and as such its transmitted power (intensity of light) is smaller. On the other hand, in a network composed of few base stations, each station needs to cover a larger area and as such transmit more power, such that the exposure will be higher in its proximity. Therefore, increasing the number of base stations in 5G allows for a reduction of exposure to radiation, as already demonstrated in previous studies; in addition, this increase enables network operators to manage the networks more efficiently with consequent benefits for users: higher bandwidth availability and support for a larger number of simultaneous accesses.

HIGHER FREQUENCIES

The use of frequency bands higher than in previous generations has been pointed out by those who criticize 5G as a possible health risk factor. In fact, 5G takes advantage of a wider set of frequencies than 4G, more specifically between 700 MHz and 3.6 GHz, while 4G uses frequencies between 800 MHz and 2.6 GHz, therefore 5G uses both upper and lower bands than 4G. In both generations, the upper bands are intended to allow for higher data-rates while the lower ones allow for more extensive network coverage, in particular in rural areas. However, we should remember that nowadays we use widely Wi-Fi networks that operate around the 5.5 GHz band, so the 3.6 GHz band from 5G does not represent anything particularly new to the body of knowledge on the use of different frequencies. Critics also point as concern the use of millimetre waves in 5G (from 28 GHz and upper bands), however, these are not expected to be rolled out anytime soon in Europe, and it is known that these will use very low powers (in small coverage cells), so these will be of low risk in terms of exposure.

CONCLUSIONS

In conclusion, there is no evidence of any health risks resulting from exposure to radiation associated with 5G communications networks or even from previous generation networks. In a final note, we should remember that mobile communications represent only one of the sources of electromagnetic radiation, among the several existing sources (such as FM and television broadcast), and therefore the subject of radiation exposure should always be analysed as a whole considering the various sources. We are certain that the scientific community will continue to investigate possible effects on both health and environment, and will be permanently alert and ready to clarify the public.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THz wireless communications:
CHALLENGES AND PARADIGM SHIFT

Information and Communication Technologies (ICT) have a significant impact in several aspects of modern society, facilitating the vision of ubiquitous communication and the internet of things.

HENRIQUE SALGADO [1,2]
[1] INESC TEC
[2] FACULTY OF ENGINEERING OF THE UNIVERSITY OF PORTO
henrique.salgado@inesctec.pt

ICT has and will continue to have a substantial influence on the way we communicate, how information is disseminated, the way we work and conduct business, social life, and ultimately on the macroeconomic growth. All these factors, in turn, affect society enabling improvements in infrastructure and standard of living. The challenges of the growing need for bandwidth, and the evolution of several generations of communication systems – 3G to 5G – have been achieved as a result of the interplay between technologies based on optical systems (high speeds at a global level on the planet) and ubiquitous communication facilitated by wireless radio-frequency communication systems and more recently mobile communications between vehicles and via satellite.

Whereas 5G is focused on facilitating real-time video streaming, building on the efforts of 4G to provide low-cost data capacity (and free voice), 6G will target augment intelligence and human experience requiring even wider bandwidths. We see a trend that is the increase of bandwidth to serve new use case scenarios. It is envisaged that mobile service data rates will be comparable to wireless LAN by 2035 (see Figure 1).

To meet this need for higher communication speeds, one approach would be to increase the spectral efficiency by increasing the order of the modulation format being used, which demands higher output powers and larger signal-to-noise ratios, which is difficult to achieve, hence not desirable. An alternative solution is to increase the available bandwidth by exploring other frequencies of the electromagnetic spectrum. This is where the THz band comes into play.

THz communication is a general designation of wireless communications using the band of the electromagnetic spectrum between 100 GHz to 10 THz. This band is not restricted to communications. In effect, the THz band opens up room for tremendous potential applications, including high-precision radars, non-destructive testing and material characterization, biomedical imaging and medical diagnosis. Remember that high frequency means lower wavelength, hence higher accuracy, so the listed applications should be of no surprise. The emphasis here will be on the THz waves for wireless communications, which are expected to play a major role in the 6th generation of wireless standard (6G), enabling high-speed wireless links with data rates above 100 Gb/s with low latency, besides the high accuracy localization and sensing.

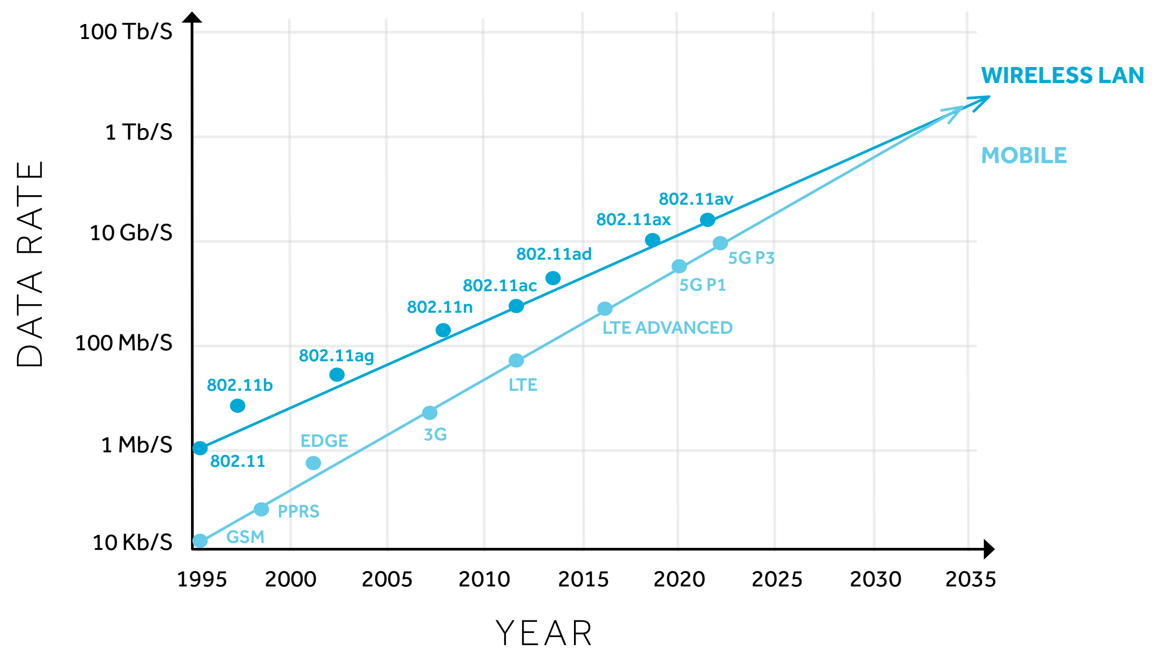


Figure 1 - Wireless LAN and mobile evolution (adapted from [Elayan, 2019]). Adapted by INESC TEC.

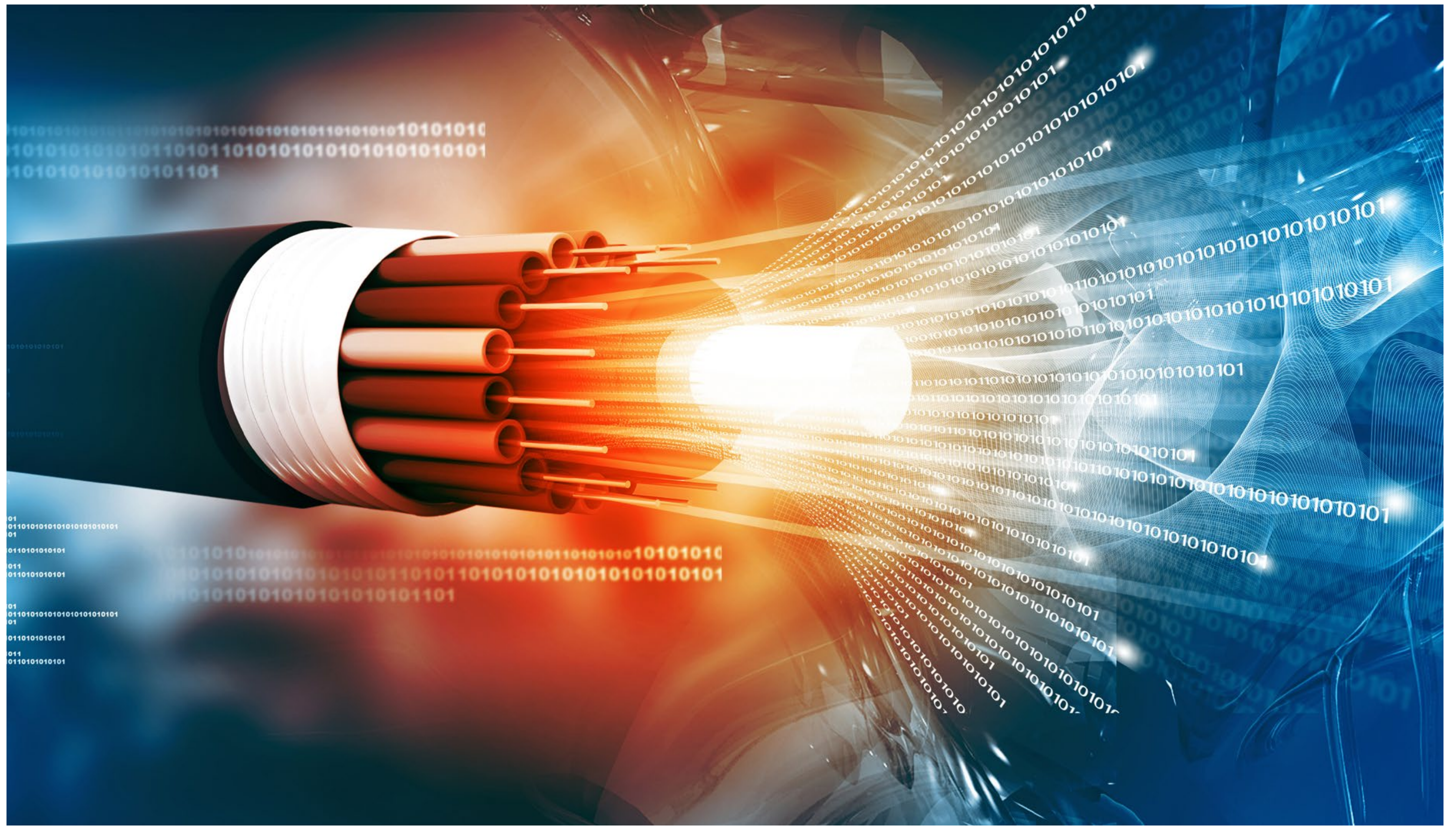
The IEEE standardization effort 802.15.3d recently assigned the frequency band between 252.72 GHz and 321.84 GHz to wireless communications, which proves the growing interest in THz communications. The standard includes 69 overlapping channels and 8 supported channel bandwidths from 2.16 GHz to a single 69.12 GHz channel.

However, to be able to access this still relatively "unchartered territory", some significant technological challenges still need to be overcome

- High level of free space loss;
- The availability of high-power electronic THz sources suitable for modulation;
- Beam steering capability to establish point to multipoint links;
- Signal conditioning and processing;
- High-speed electronics;
- Low cost and small form factor produced in a scalable technology.

In the microwave/mm-wave range, even for a distance of 100 m the loss can be as high as 130 dB at 1 THz, which is approximately 100 000 times higher than at 2.4 GHz. When combined with the lack of high-power emitters (known as the "THz gap"), the loss factor is a major issue due to the inefficiency of photonic and electronic devices in the THz band operating at room temperature. That could be addressed, for example, by using multiple sources coupled to antenna arrays with additional signal conditioning to control the direction of the beam (either electronic or photonic) and establish point to multipoint communications. In this instance, package integrated antenna design is a research topic by itself, with its own challenges.

Still, high-speed electronics are required. Current efforts point to the use of low-cost and high-level integration of CMOS SiGe-HBT (Silicon-Germanium heterojunction bipolar transistor) that is already capable of operating at maximum cut-off frequencies, fmax, of 750 GHz [Heinemann, 2016]. SiGe combined with III-V of semiconductor technology will enable higher output powers and low noise-figures. It is not possible to mention all the research directions, which are many and include, among others, the use of new materials, e.g., graphite and metamaterials to enhance the device or antenna performance. The combination of photonic and



[1] CMOS SiGe-HBT, do inglês *Complementary metal-oxide-semiconductor* (CMOS), ou metal-óxido-semicondutor complementar, e *silicon-germanium* (SiGe) *heterojunction bipolar transistor* (HBT), transístor bipolar de heterojunção de silício-germânio.

electronic technologies exploiting the benefits of each family of devices will ultimately lead to THz systems with the highest performance possible with wide bandwidth, high spectral purity, extensive dynamic range and tuning range, power amplifying capability and ease of functional on-chip integration [Nagatsuma, 2016]. Also, photonics is directly compatible with the existing fibre optic network allowing seamless integration. As an illustration Figure 2 depicts the use of resonant-tunneling diodes with integrated photodetectors (RTD-PD), operating as optoelectronic transceivers in high-speed wireless systems [Zhang, 2019].

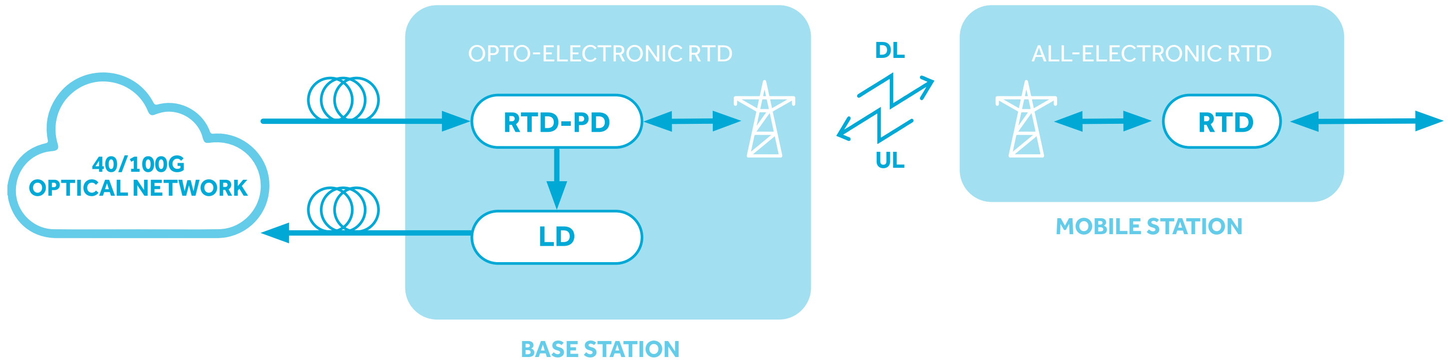


Figure 2 - Seamless integration of optoelectronic transceivers in high-speed wireless systems (DL-Downlink, UL-Uplink, LD-Laser diode). Adapted by INESC TEC.

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DRONES IN 5G COMMUNICATIONS

The use of drones in 5G and beyond-5G communications has been gaining prominence in recent years, enabling new application scenarios that require an on-demand temporary network infrastructure. The ability of drones to carry 5G base stations on-board allows the implementation of a dynamic and intelligent network infrastructure that adapts to the position and traffic demands of its users. This concept is the basis of multiple scientific contributions of INESC TEC associated with research projects and PhD theses.

EDUARDO NUNO ALMEIDA [1,2]
HELDER FONTES [1,2]
[1] INESC TEC
[2] FACULTY OF ENGINEERING OF THE UNIVERSITY OF PORTO
eduardo.n.almeida@inesctec.pt
helder.m.fontes@inesctec.pt

The current paradigm of permanent communications anywhere and anytime poses scientific and technological challenges in the planning and efficient implementation of mobile communications networks. There has been a growing need for better coverage, higher throughputs, lower latencies and greater density of connected devices. These requirements have traditionally been addressed assuming the planning of a fixed infrastructure, with a capacity scaled to support the network's peak use, which can translate into an inefficient use of the network's resources for most of the time. With fixed base stations, it is necessary to plan their (fixed) positioning, the antenna apertures, the radio channel configurations and the transmission power to create radio coverage cells with well-defined positions and ranges, which minimize interference with neighboring cells. With each new generation of mobile communications, there has been an increase in the offered quality of service (QoS), which has enabled the emergence and massification of new types of connected mobile services. In the case of 5G networks, they were planned to support new types of applications with more demanding throughput and latency requirements, compared to those that are possible to achieve in 4G networks. New application types include virtual / augmented reality, telepresence through holograms, telemedicine, real-time remote control of robots for search and rescue operations, among others.

However, some scenarios pose special challenges due to the unpredictability of their users or external factors, for example, emergency scenarios and spontaneous concentrations of people at events. In emergency scenarios, such as fires, earthquakes and floods, multiple teams of first responders move while fighting the emergency, and they need to communicate among themselves and with a central command station. In some cases, the existing infrastructure may not be operational due to damage caused during the emergency, which translates into a lack of mobile network coverage in those sites. Other cases may require an accurate control of search and rescue robots with low latency links and sufficient throughput for high quality video streaming. In scenarios of spontaneous concentrations of people at events, such as festivities or outdoor events – e.g.: festivity of São João, demonstrations and peregrinations –, high volumes of traffic may be generated due to live streams to social networks, video calls and multimedia content consumption. The spontaneity of the event, along with the high utilization of the mobile network's resources and the unpredictable behavior of the crowd, may lead to the congestion of the existing infrastructure. In these unpredictable scenarios, there is a need to create an on-demand temporary network infrastructure to complement the existing one.

5G networks are the first to be planned in advance to enable the use of drones to provide or enhance wireless coverage in a myriad of scenarios. The drones are equipped with 5G base stations that forward traffic from user terminals to other 5G base stations in line of sight or using other network technologies that allow access to the operator's mobile network.

The use of drones to carry 5G base stations allows the creation of a dynamic network infrastructure, since drones can quickly move in the 3D space. The dynamic positioning ability translates into an optimization of the QoS offered to users, since the flying base stations can be repositioned over time to ensure coverage and meeting the users' QoS requirements. This QoS optimization results from the optimization of the access network – the link between the drone and the users – and the backhaul network – the link between the drone and the infrastructure. In terms of the access network, flying base stations can be positioned closer to the users that generate more traffic, in order to increase the effective network capacity in scenarios of spontaneous concentrations of people, or teams of first responders in emergency scenarios that require permanent network coverage. In terms of the backhaul network, drones can be positioned as relay nodes between users and remote base stations, enabling the establishment of a wireless link between them that overcomes existing obstacles (such as trees, buildings or mountains).

Despite the advantages of using drones to create a flying and dynamic network infrastructure, their use presents some known challenges that can be overcome depending on the application scenario. One of these challenges relates to the autonomy of drones, especially the electric ones, which is limited by the capacity / weight ratio of the batteries used both for propulsion and for powering on-board equipment. In certain scenarios, this limitation can be overcome considering that drones can land on surfaces near the users, avoiding hovering in the same position. Moreover, drones can be tethered (to a land vehicle, for example) with a cable that powers the drone, allowing permanent flight with more limited mobility. Finally, current legislation limits the use of drones, namely by prohibiting flying over crowds. In the latter, directional antennas can be used to cover areas around the drone more effectively, thus avoiding flying over people.

In conclusion, the ability of drones to create an on-demand network infrastructure to provide or enhance 5G mobile network coverage, which dynamically and intelligently adapts to the needs and requirements of its users, has established itself as a novel concept with applications in multiple sectors of the modern society. The scientific, technological and legislative challenges associated with the use of this equipment create multiple research opportunities to develop novel solutions that are more efficient, safer and greener, with the ability to meet the requirements of current and future generations.

ARTIFICIAL INTELLIGENCE:

THE ANNOUNCED REVOLUTION IN COMMUNICATIONS

Artificial Intelligence (AI) is currently changing our everyday life in multiple domains, be it in the form of personal assistants, autonomous cars, or smart texting. This powerful technology will now be embedded in the communications networks that are the nervous system of the digital world in which we are immersed.

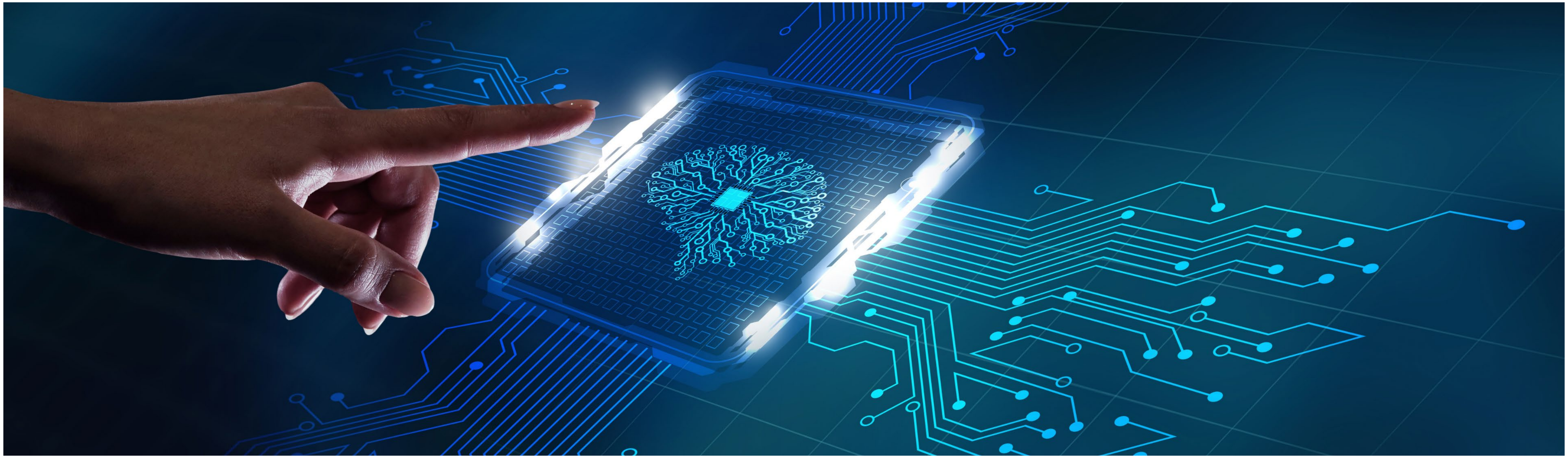
MEHDI BENNIS [1]
RUI CAMPOS [2,3]
[1] UNIV. OULU
[2] INESC TEC
[3] FACULTY OF ENGINEERING OF THE UNIVERSITY OF PORTO
mehdi.bennis@oulu.fi
rui.l.campos@inesctec.pt

AI will indeed be crucial for next generation networks. It will be there by design and enable network self-management and self-control towards fully autonomous networks operating similarly to other autonomous systems such as autonomous cars and autonomous aircrafts. For example, through AI the creation of the so-called network slices in 5G – i.e., application-oriented virtual networks over the physical infrastructure – will be fully autonomous, towards the intent-based networking paradigm envisioned for 6G.

The need for AI in next generation networks comes from the ever-increasing complexity of the underlying technologies, including an ever-increasing number of parameters that can be controlled and whose optimization according to the networking context is yet to be explored. Also, there is a need for making networks efficient and scalable from multiple perspectives including performance, energy consumption and privacy. This complexity leads to an increasing need for holistic solutions that take advantage of AI techniques and of the available computational capacity, either in the cloud or in the edge, as the only means to self-optimize the network operation dynamically and in real-time.

To solve this massive scalability challenge while addressing privacy, latency, reliability, energy and bandwidth efficiency, machine learning at the edge is of utmost importance! To date, progress in AI/Machine Learning (ML) has been driven by the availability of huge amounts of data and computing power, where a single powerful server typically located in a centralized and remote data center has access to a global dataset. However, the new breed of intelligent devices and mission-critical applications cannot rely on cloud-based AI/ML due to their real-time characteristics, intolerance to long latency, and high reliability. This has led to a huge interest in Federated Learning (FL), a new paradigm in which training data is stored across a large number of geographically dispersed devices.

Federated Learning (FL) is a distributed machine learning training framework, originally proposed by Google with use cases spanning a whole range of fields and applications, such as healthcare, intelligent transportation, industrial automation, and telecommunication networks.



FL is designed to periodically upload devices' model parameters (e.g., neural networks weights), during local training, to a parameter server that performs model averaging and broadcasts the resulting global model to all devices. FL is about training a high-quality centralized model in a decentralized manner – where training data is unevenly distributed, never leaves the device and every device has access to a tiny fraction of it –, while taking into account constraints in terms of bandwidth, convergence time (latency), energy and so forth.

There are several advantages in using this approach:

1. Local inference at the network edge is bandwidth-efficient, reduces latency and enhances reliability. Rather than sending data to the cloud, inference is run directly on the device, and data is sent to the cloud only when additional processing is required;

2. Making inference accurate and fast is instrumental in swiftly responding to local critical events;

3. Device-generated private data can be utilized for training, while keeping data locally on the device, and the global model is learned by aggregating locally computed updates among devices or via a parameter server (base station, access point or any infrastructure node).

There are a myriad of challenges facing FL that must be addressed in terms of training algorithms, architectures, network topologies and conflicting requirements. For instance, a learning model may have a million parameters (as in self-driving vehicles), and hence a model update can be bandwidth-consuming, especially for thousands of IoT devices. Slow devices can undermine the training process due to poor computing capabilities or poor path-loss to the federating server. While vanilla FL is essentially about training a global model, adapting to local dynamics and generalizing to other tasks is key. FL is essentially a semi-centralized solution with a single point of failure, calling for a fully distributed and scalable learning framework. Moreover, since devices are resource-constrained, on-device FL must go beyond accuracy maximization and explore the entire gamut of accuracy, energy, robustness, and privacy tradeoffs.

Unlike centralized AI/ML, in edge AI/ML training, the data samples are generated and privately owned by each device. In this case, direct data sample exchange may be prohibited; hence, each device's current model needs to be shared over stochastic and intermittent wireless links, subject to devices' resource constraints and privacy guarantees.

Furthermore, in contrast to centralized ML in which the training dataset is independent and identically distributed (IID), data is likely to be non-IID which may hinder convergence. Owing to the distributed nature of the data, wireless connectivity between the helper and devices and/or among devices may be intermittent, bandwidth or interference limited, hindering training convergence and the overall system performance. To address such problems, joint scheduling of devices can be used, transmitting only informative models instead of transmitting model updates at every time-slot, exploring peer-to-peer learning instead of solely focusing on centralized topologies, and the list goes on. These are the challenges the community will continue addressing in the future.

Edge AI will play a pivotal role in 5G and 6G, namely when it comes to the distributed, autonomous management and control of the network, towards the intent-based networking paradigm. Yet, cloud AI and the upcoming quantum AI will be crucial to solve problems that we cannot solve today and to complement edge AI. In order to continue to do so, a holistic approach is needed, not focusing exclusively on maximizing the learning accuracy and predictions, but also considering the impact on energy efficiency, resiliency, privacy, scalability and accessibility. This will be of utmost importance to bring new impactful players to AI/ML applied to communications networks and reduce the time and energy consumption of the training process of the AI models.

THE ROAD TO 6G

As the fifth generation (5G) of mobile communications systems starts being commercially deployed, the research community has shifted its focus towards the study of fundamental solutions for the 2030 era, i.e. 6G.

MATTI LATVA-AHO [1]
ARI POUTTU [1]
RUI CAMPOS [2,3]
MANUEL RICARDO [2,3]
[1] UNIV. OULU
[2] INESC TEC
[3] FACULTY OF ENGINEERING OF THE UNIVERSITY OF PORTO
matti.latva-aho@oulu.fi
ari.pouttu@oulu.fi
rui.l.campos@inesctec.pt
manuel.ricardo@inesctec.pt

AIt is not yet clear what 6G will entail exactly, but it will certainly include relevant technologies considered immature for 5G including those related to the way data is collected, processed, transmitted and consumed within the wireless network. New Key Performance Indicators (KPI) drivers will be needed which complement and improve the already challenging 5G-related KPIs. Societal megatrends and United Nations sustainability goals, including lowering Green House Gas (GHG) emissions, emerging new technical enablers as well as ever-increasing productivity demands are also key 6G drivers.

The International Telecommunication Union (ITU) – the United Nations standardization body for information and communication technologies – started recently to shape the 6G vision. The ITU vision shall be ready by 2023 and will be followed by the identification of the requirements for the mobile communications system. 6G research will certainly look into the challenging requirement of enabling mobile data rates up to 1 Tbit/s per user. This will be possible through the efficient utilization of the spectrum in the THz frequency bands, which, in turn, will potentiate the merging of communications with sensing and 3D imaging by taking advantage of the micrometer wavelengths.

New services augmenting the human communication potential such as telepresence and mixed reality will be made possible by means of high-resolution imaging and sensing, accurate positioning, wearable displays, specialized processors and high-performance wireless networks. Current smartphones will be replaced by pervasive Extended Reality (XR) experiences with lightweight glasses delivering unprecedented resolution, frame rates, and dynamic range – e.g. Facebook and Ray-Ban have recently released their first "smart glasses" [1], which represent a remarkable step towards this vision. Humanoid robots and cyberpets will also make part of our daily lives and communicate with us using natural language.

In the Internet of Things, the emergence of a huge number of different types of devices and applications demanded by multiple verticals will set further diversifying system requirements. Machine type communications with real-time sensing capabilities and different data rates and total capacity requirements will set new challenges to the overall communications system. At this early stage of 6G development, the research community should take a bold approach to look at alternative system architectures and service delivery mechanisms underneath. This is the right time to critically challenge current 5G systems network architectures and try to find alternative models for network operation.

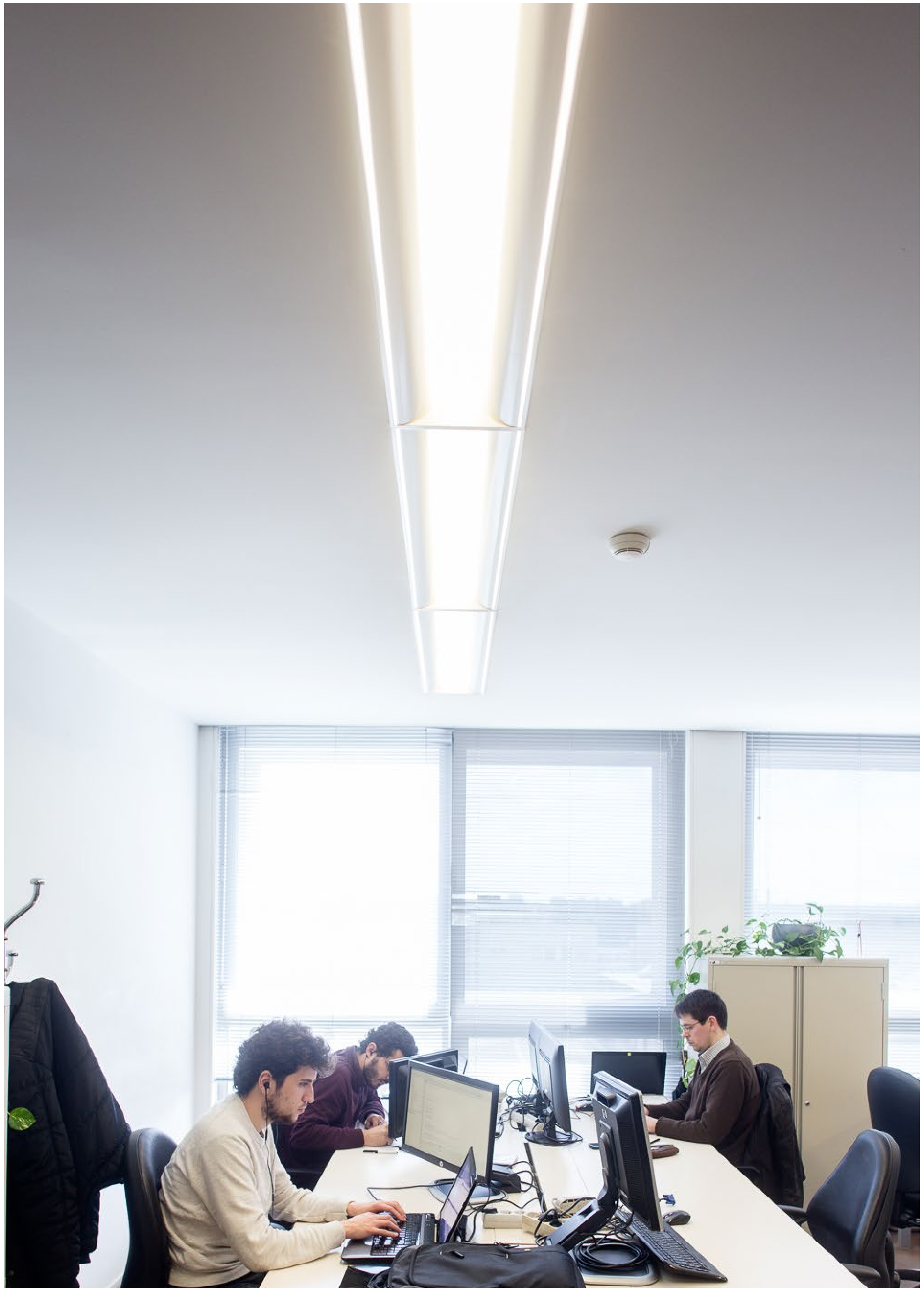
[1] https://www.theguardian.com/technology/2021/sep/09/facebook-stories-social-media-firm-launches-ray-ban-smart-glasses [Accessed: 10th Sep. 2021]

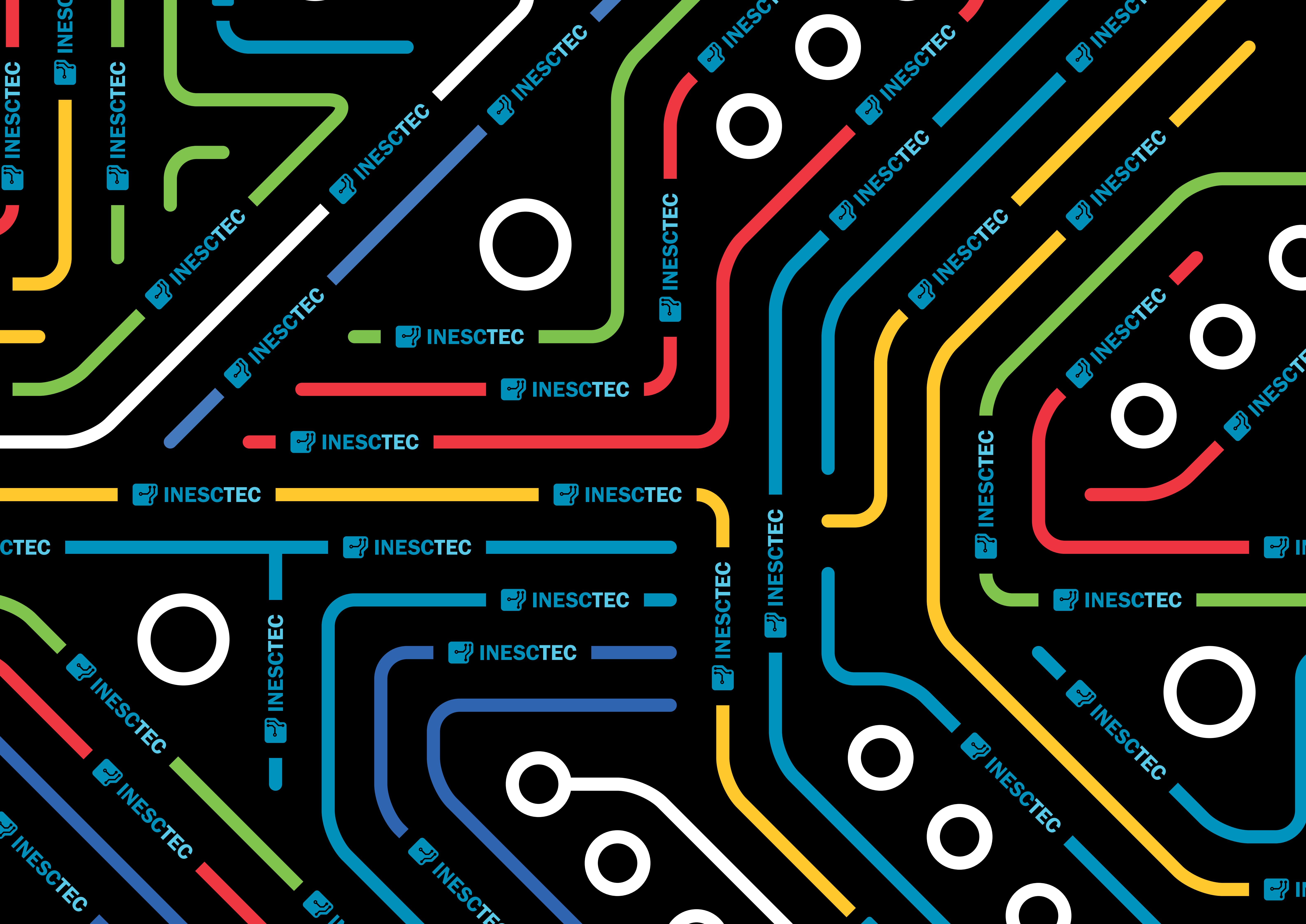
Our society is increasingly relying on digital automated services hidden from humans. The fourth industrial revolution will be a reality by 2030, characterized by automated processes, distributed, operating in real-time, driven by artificial intelligence, and demanding permanent wireless connectivity. Connectivity everywhere and at all times will be as important as having electricity. In this scenario, it becomes irrelevant who builds connectivity, who owns the networks, or who owns the spectrum licenses. Ubiquitous networks will be built by different operators for different purposes. Local specialized services with various connectivity mechanisms will become popular. At the same time, large coverage area networks will be needed for reliability and service continuity, including Satellite. Therefore, growing needs for local specialized services and networks need to be potentiated, but at the same time we need to make sure that large area mobile network operators (MNOs) will not be threatened as the global coverage relies completely on them. Hence, future needs may cause some conflicts of interests, which will have to be sorted out.

The 5G promise was to enable all facets of society with digital services by connecting things and processes to the networks. However, it appears that similarly to earlier mobile generations, even though a new mobile cellular G emerges every ten years, the market transformation takes 20 years to fruition. This is evidenced by the slower than expected take-up of new wireless services in vertical business areas in the 5G era and the expectation that 6G will provide the connected digital services in large scale.

The 5G/6G technological and architectural features that will shape the new access, networking, and management domains in mobile communications promise countless opportunities for service innovation and business efficiencies, creating an unprecedented impact on multiple vertical sectors. The role of 5G/6G is to cognitively connect every feasible device, process, and human to a global information grid. We are therefore only now at the brink of an information revolution, and new digitalization markets will offer significant revenue expansion possibilities for those who react fastest to new opportunities.

Portugal has been recognized as an early adopter of new technologies and the Portuguese are known to love using them. There is an unexpected delay in deploying 5G but, since the main characteristics of 6G rely on the experience of using 5G, it is important that Portugal deploys, as fast as possible, a set of communications living labs focused on the vertical areas of economy including industry, agro-food, sea, logistics, health, and mobility corridors. A structured policy should also be implemented for studying and defining 5G/6G networks and services along with its impact on the country's digitalization and creation of green solutions.




INESCTEC

4

CURRENT THEMES

COMMENTS ON THE RECENT EVOLUTION OF THE ELECTRICITY MARKET PRICE IN THE IBERIAN ELECTRICITY MARKET

One can perceive the Iberian Electricity Market, MIBEL, as an evolution of the Spanish electricity market that started its operation in January 1998. In November 2001, the Portuguese and the Spanish governments signed a cooperation protocol for the establishment of an electricity market at the Iberian level that would hopefully start operating two years later.

JOÃO TOMÉ SARAIVA [1,2]
JOSÉ VILLAR COLLADO [1]
[1] INESC TEC
[2] FACULTY OF ENGINEERING OF THE UNIVERSITY OF PORTO
joao.tome.saraiva@inesctec.pt
jose.villar@inesctec.pt

1. Background

However, it was only on the July 1st, 2007, that MIBEL was in full operation with the common day head market operator. Currently, MIBEL includes several trading platforms: the day ahead market, the intraday auction market, the intraday continuous market -all of them managed by the OMIE (the Spanish pole of the Iberian Electricity Market Operator) -, a derivatives market managed by OMIP (the Portuguese pole of the Iberian Electricity Market Operator) and more specific markets managed by the Portuguese and the Spanish Transmission System Operators, TSOs, to procure and contract reserves. Among all these platforms, the day ahead market is, by far, the more liquid trading mechanism and also the one that is responsible for the largest traded electricity and economic volume (about 90% of the electricity traded in MIBEL is traded in this market). For this reason, in the rest of this paper, we will focus our analysis and comments on the MIBEL day ahead market.

As the name suggests, the day ahead market opens the day before delivery and the Iberian Market Operator accepts buying and selling bids communicated by the registered market agents till 12 p.m. (Spanish hour). In its simplest version, these bids correspond to pairs of quantities and prices communicated by each agent for each hour of the next day. The selling bids include the quantity each generation company or power station admits selling at each hour, together with the minimum price they want to receive. On the other hand, the buying bids include the quantity each consumer or retailer agent wants to buy at a given hour, together with the maximum price they admit paying at that hour. If no more information is available, the Market Operator orders the selling bids for hour h by the ascending order of the bid prices, creating the aggregated selling curve, and the buying bids by the descending order of the bid prices, thus creating the aggregated buying curve. The intersection of these two curves yields the traded quantity and the market price at hour h. This exercise can be translated into a Linear Programming problem in which the so-called Social Welfare Function, SWF, is maximised - which can be interpreted as the area between the two mentioned aggregated curves. Figure 1 illustrates these curves for hour 20 of July 10, 2019. At this hour, the intersection point B indicates that 31381,1 MWh were traded, and the market price was 53,92 €/MWh.

This figure is useful to highlight two important points:

- In the first place, the bids described above are called Simple Bids and they implicitly mean that each agent communicates quantities and prices for hour h regardless of the bids for the previous and subsequent hours. Ultimately, this means that the optimisation problem to solve for an entire day is separable in each of its 24 hours, and that the Market Operator would in fact solve 24 separate problems, one per hour. Hence, market agents, namely generation agents, can communicate complex bids if they include extra information related, for instance, with ramps or the minimum income the generation company or unit wants to receive throughout the day. This extra information is translated into the optimisation problem as extra constraints that ultimately degrade the solution that would be obtained if only simple bids were considered. In figure 1, this mechanism explains the presence of two selling curves. The one in light green was built just considering simple bids, while the dark green already considers extra complex bid information. This process can be interpreted as if the light green curve was shifted to the left because some bids were eliminated from the matching process, since they didn't comply with the specified complex bid constraints. As a result, the market price rises from 43,00 €/MWh to the final value of 53,92 €/MWh (that is, from point A to point B;
- Secondly, this trading mechanism corresponds to a uniform price auction, meaning that regardless of the bid prices, at the end, when the market clears, all generators whose bids were accepted (the ones on the left side of point B) will receive the market price and all consumer and retailer agents whose bids were accepted (once again, the ones on the left side of point B) will also pay the market price. As an illustration, this means that at this hour of July 10, 2019, there were 14728 MWh that bid at 0,00 €/MWh, and that all these zero price selling bids were accepted, with this energy paid at 53,92 €/MWh.

It is important to emphasise that uniform pricing is very often preferred to the pay-as-bid mechanisms, due to theoretical and practical reasons[1]. On the one side, uniform pricing allows generation units to bid at their marginal or opportunity costs, while in a pay-as-bid mechanism they bid at their own estimate of the market price, hiding their true marginal costs. This can lead to suboptimal dispatches and a less efficient system operation since units that are more expensive could be producing instead of cheaper ones. On the other side, and under simplifying assumptions, one could prove that, for adapted systems (when investments have been done in a theoretically optimal way), the extra margin the generation units get when the market price is larger than their marginal or opportunity costs (at which they price their energy), allows them to recover the investments costs[2]. In fact, marginal theory says that there should be hours with non-supplied energy (where the price is set by the last supplied demand), so that the marginal units (those more expensive cleared) that set the market price at their marginal or opportunities costs, could recover their investments costs. However, there is a clear debate about this question, since reality is always much more complex: power systems are not adapted, their oligopoly structure limits competition, there is often an excess of installed generation capacity promoted by regulators to avoid shortages, and generation units do not always recover their investment costs (known as the missing money problem).

The market prices depend on the demand, the technologies mix to supply this demand and their marginal or opportunity costs, as well as on the available primary resources (namely water, wind and solar radiation). To illustrate these variations, Figure 2 presents the hourly prices on July 10, 2019, and Figure 4 corresponds to December 22, 2019. The prices in Figure 2 correspond to a summer day in which there is typically more reduced wind and hydro generation, as can be seen in Figure 3, so that more costly generation technologies (with the combined cycle units setting the price in all hours) are used more intensively throughout the day. As to December 22, 2019, we are talking about a very windy and rainy period, with less costly energy available all through the day, with no fossil fuel plants producing, leading to null or very close to null prices for all hours. The generation mix for this day is presented on Figure 5.

Buying and selling aggregated curves
Hour 20 - 10/07/2019

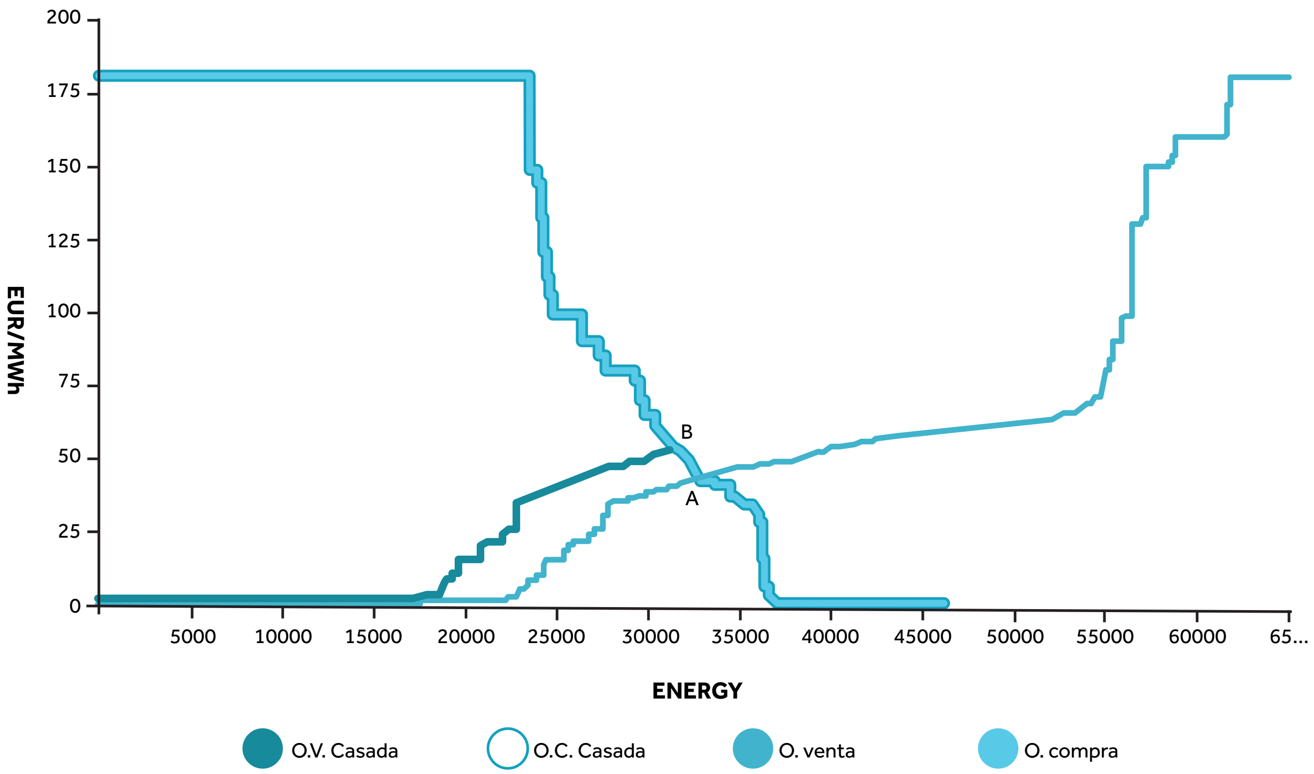


Figure 1 -Buying and selling aggregated curves for the hour 20 of July 10, 2019. Original from OMIE | Adapted by INESC TEC.

Day-ahead hourly prices
10/07/2019

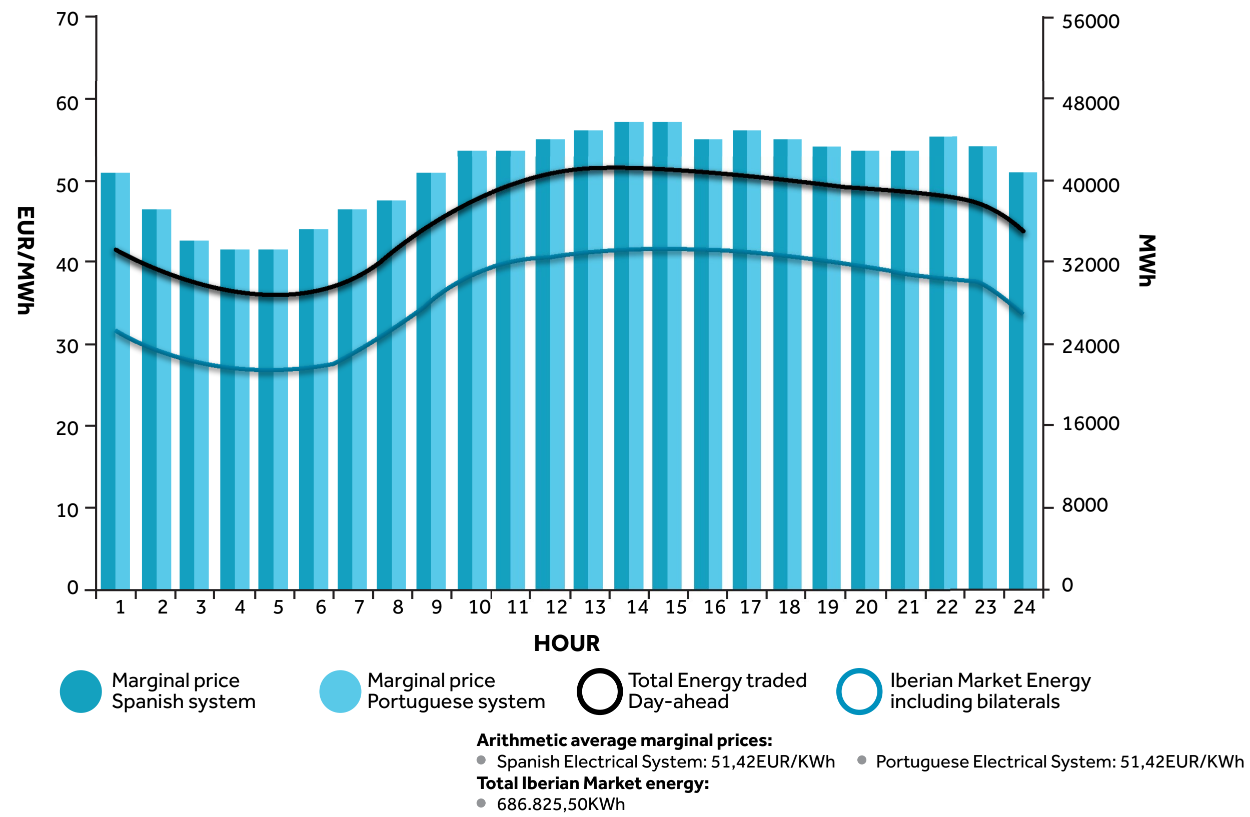


Figure 2 - Hourly prices and traded energy for July 10, 2019[3]. Original from OMIE | Adapted by INESC TEC.

[1] A. E. Kahn, P. C. Cramton, R. H. Porter, and R. D. Tabors, 'Uniform Pricing or Pay-as-Bid Pricing: A Dilemma for California and Beyond', The Electricity Journal, vol. 14, no. 6, pp. 70–79, Jul. 2001, doi: 10.1016/S1040-6190(01)00216-0.

[2] Regulation of the Power Sector | Ignacio J. Pérez-Arriaga | Springer. Accessed: Apr. 18, 2017. [Online]. Available: http://www.springer.com/gp/book/9781447150336

[3] OMIE, 'OMIE (market results download)'. http://www.omie.es/aplicaciones/datosftp/datosftp.jsp (accessed Oct. 31, 2018).

Hourly power by technologies
Mibel - 10/07/2019

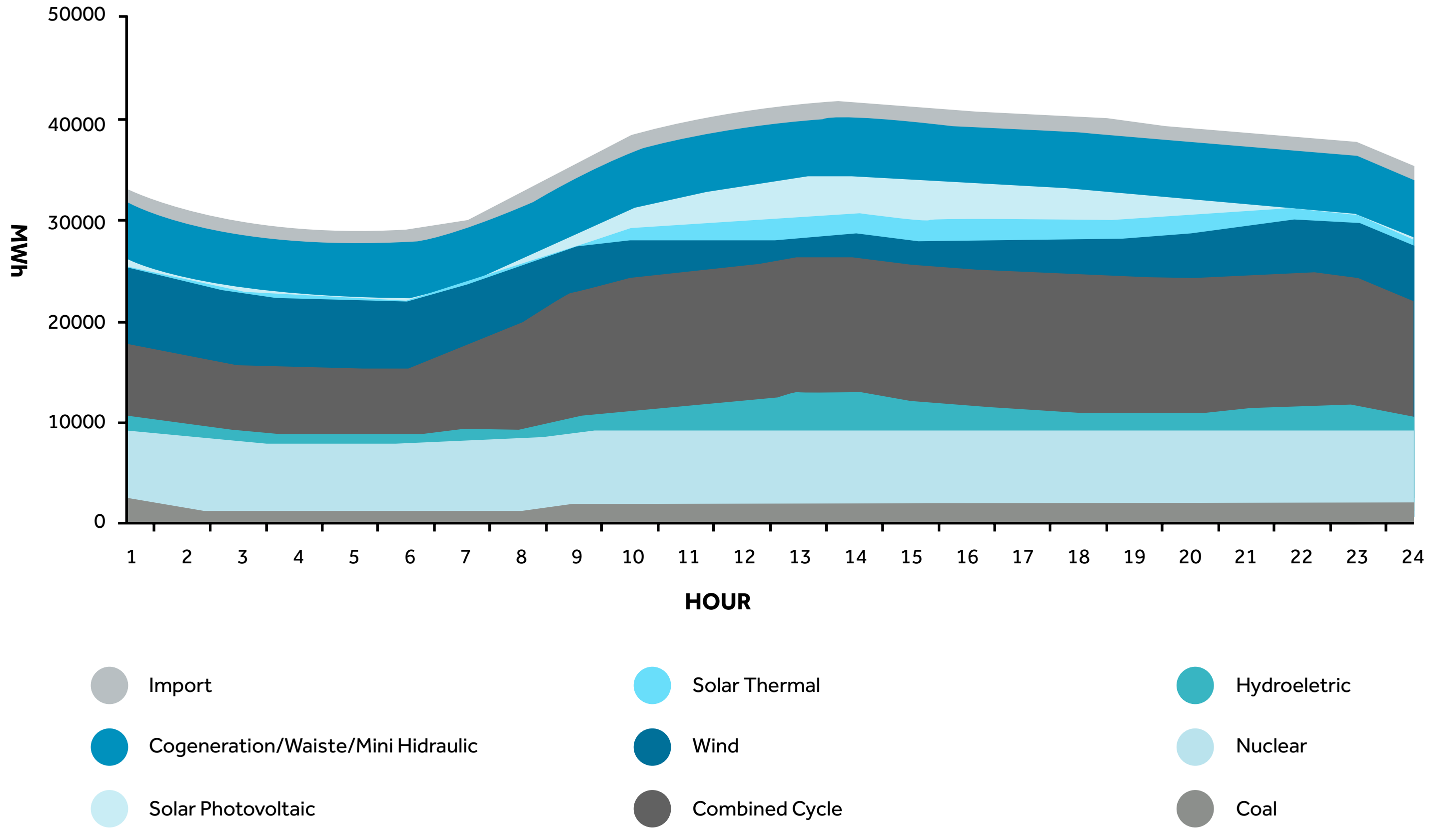


Figure 3 - Hourly generation per technology for July 10, 2019[3]. Original from OMIE | Adapted by INESC TEC.

[3] OMIE, 'OMIE (market results download)'. http://www.omie.es/aplicaciones/datosftp/datosftp.jsp (accessed Oct. 31, 2018).

Day-ahead hourly prices
22/12/2019

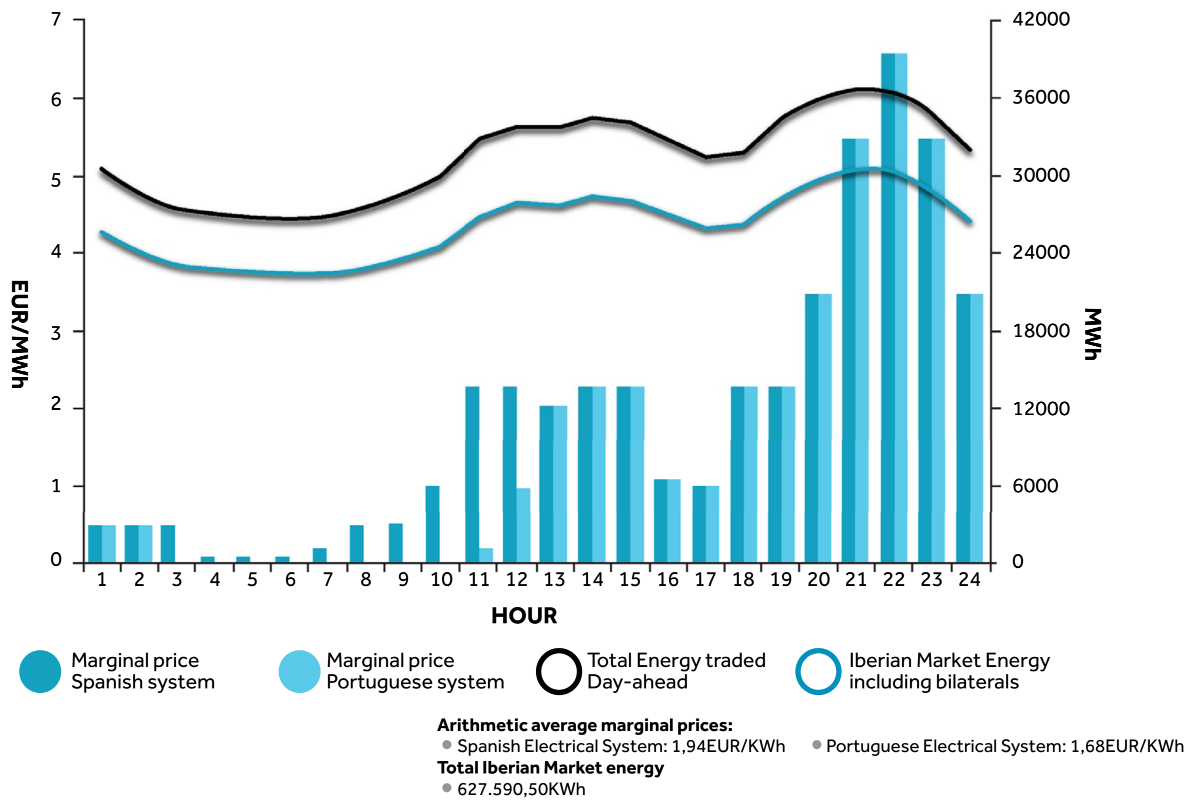


Figure 4 - Hourly prices and traded energy for December 22, 2019[3]. Original from OMIE | Adapted by INESC TEC.

Hourly power by technologies
Mibel - 22/12/2019

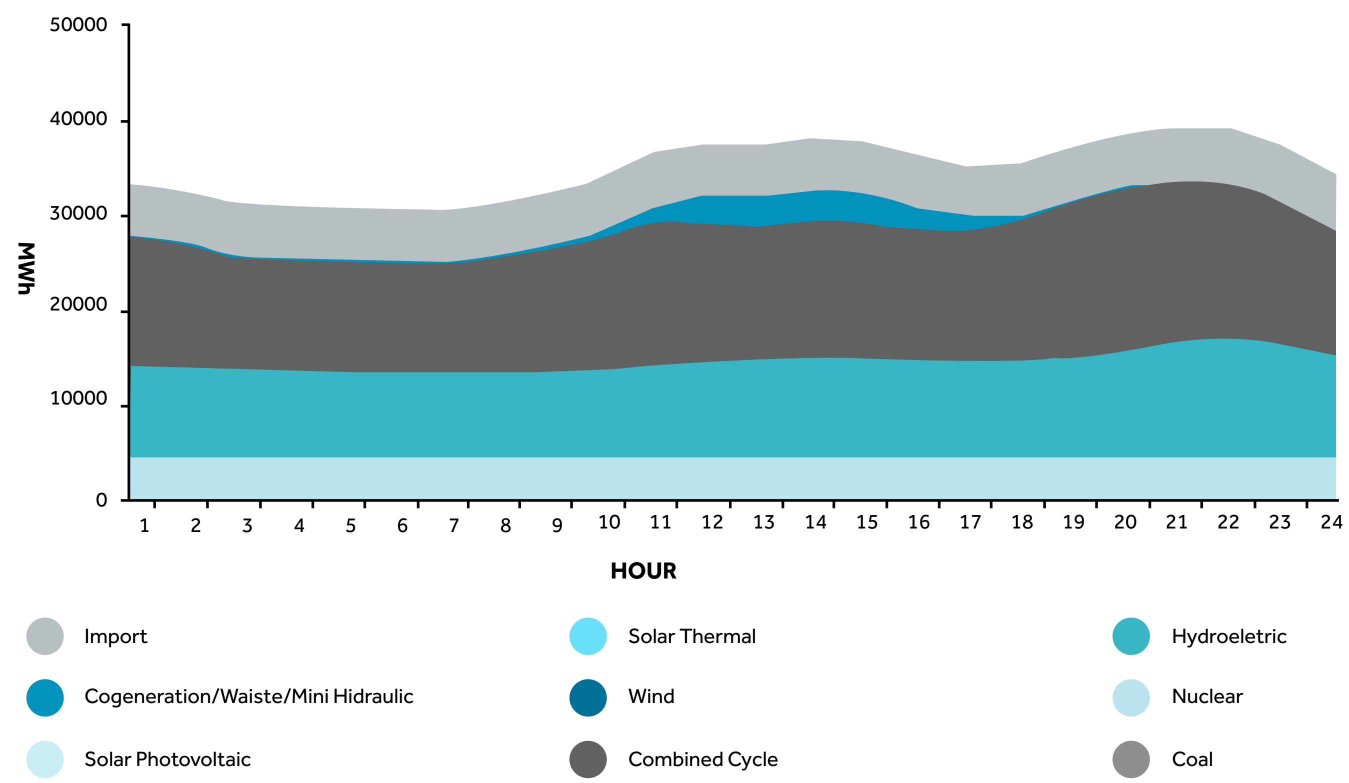


Figure 5 - Hourly generation per technology for December 22, 2019[3]. Original from OMIE | Adapted by INESC TEC.

2. Evolution of the generation systems of Portugal and Spain

As mentioned before, the market prices are influenced by the bid prices, namely by the generation bid prices. In general, these bid prices follow the operation marginal costs associated to each technology and these values are interpreted as the cost of generating an extra quantity of 1 MWh, admitting that the generator is operating at a certain level. However, dispatchable hydro generators bid at their opportunity costs, which reflect the potential benefits of offering the same energy at some other particular point in time - which is typically the marginal cost of the technology that hydro is going to replace. According to the primary resources that are used by each technology, generators have different marginal costs from very low or virtually zero for nuclear power stations, wind, and PV units, run of river hydro units and geothermal units, to higher values for thermal fossil fuel generators, namely coal, natural gas units and fuel generators. In view of this impact, Table I presents the evolution of the generation mix of Portugal and Spain, with the installed capacities for the most relevant generation technologies in 2010 and in 2020/21.

	Portugal		Spain	
	2010	jun/21	2010	2020
Hydro (inc. pumping and small units)	4988	7215	19552	20429
Coal	1756	576	11380	5733
Fuel/gás	1657	0	2860	8
Combined Cycle Natural Gas, CCGT	3830	3830	25235	24562
Nuclear	0	0	7777	7117
Wind	3705	5246	20057	27394
PV	134	1041	3458	11738
CSP	0	0	682	2304
Biomass	122	703	979	0
Cogeneration	1698	751	7187	5703
Other non-renewables	0	0	1050	390
Other renewables	0	28	6992	1203
	17890	19390	107209	106581

Table I - Installed capacities in Portugal and Spain in 2010 and in 2020/1 (values in MW)[4][5][6][7]. Original from OMIE | Adapted by INESC TEC.

In addition, power systems have been facing three important trends over recent years:

1. Thermal units using fossil fuels are subject to the payment of CO2 emission licences, meaning that this cost is added to the corresponding marginal cost of the fossil fuel;

2. Since coal units are the most polluting and less efficient ones, they typically require a larger amount of CO2 emission licences, which means that they became the most costly ones in the generation mix of several countries, although this could reverse depending on the gas and coal fuel prices. This means that, when building the aggregated selling curve, their bids would be in the right-hand side of the curve, so that, in many hours, these bids would not be accepted. As a result of this lower economic performance, coal power stations started to be decommissioned in many countries, similarly to what happened with the Sines (decommissioned in January 2021) and Pego power stations (planned to close in 2022), in Portugal. However, other EU countries are still building coal power plants, as it is the case of Germany, probably to maintain some energy independence after closing their nuclear plants[8], which is in fact one of the reasons behind the current high prices, as explained latter;

3. Finally, both in Portugal and in Spain, there is a clear increase of the installed capacity of renewable generation technologies, namely in large hydro units, wind parks, PV units and Concentrated Solar Power (CSP) units. According to the Portuguese Integrated Plan for the Energy and Climate 2021-2030[9], by the end of the current decade, the installed capacity in wind parks is expected to range from 8800 to 9200 MW, and from 8100 to 9900 MW concerning PV units. Regarding hydro units, the total installed capacity will increase to 9000 MW in 2030.

[4] 'REN - Eletricidade'. https://www.ren.pt/pt-PT/o_que_fazemos/eletricidade (accessed Oct. 13, 2021).

[5] Ministerio de Industria, Turismo y y Comercio, 'La Energía en España, 2010', 2011. Accessed: Oct. 11, 2021. [Online]. Available: https://energia.gob.es/balances/Balances/LibrosEnergia/Energia_Espana_2010_2ed.pdf

[6] 'Red Eléctrica de España, data on generation installed capacity'. https://www.ree.es/en/datos/generation/installed-capacity (accessed Oct. 11, 2021).

[7] REE, 'El sistema eléctrico español en 2010'. Accessed: Oct. 11, 2021. [Online]. Available: https://www.ree.es/sites/default/files/downloadable/inf_sis_elec_ree_2010_elsectorelectrico.pdf

[8] Á. Hermida, '¿Solidaridad europea? España cierra centrales de carbón, Alemania las abre', elconfidencial.com, Feb. 26, 2021. https://www.elconfidencial.com/medioambiente/2021-02-26/energia-carbon-crisis-climatica-alemania_2967356/ (accessed Oct. 11, 2021).

[9] EC, 'National energy and climate plans (NECPs)', Energy - European Commission, Jan. 23, 2019. https://ec.europa.eu/energy/en/topics/energy-strategy-and-energy-union/national-energy-climate-plans (accessed Sep. 28, 2021).

3. Evolution of the MIBEL day ahead market prices

As mentioned before, the market prices are influenced by several factors that typically determine variations along the day, the week, the month, and the year. Figure 6 presents the evolution of the average annual market price from 2007 to 2020 in Portugal (yellow curve) and in Spain (green curve). These prices were slightly different in the initial years of the common market (usually with higher prices on the Portuguese side) namely due to congestion situations in the interconnection lines between the two countries. Then, from 2009 onwards, the prices in the two price areas converged and are now the same in about 95% of the time. The average annual prices tend to be higher in dryer years, as in 2008 and 2018, given that there was less hydro generation, which typically leads to lower prices. In dryer years, there is a significant use of thermal fossil fuel generation, determining the increase of the market prices. Finally, this figure also shows the sharp decline of the average price in 2020 due to the reduction of the demand, as a result of the interruption of several economic activities from March onwards, caused by the pandemic

Day-ahead minimun, average and maximum price
Mibel

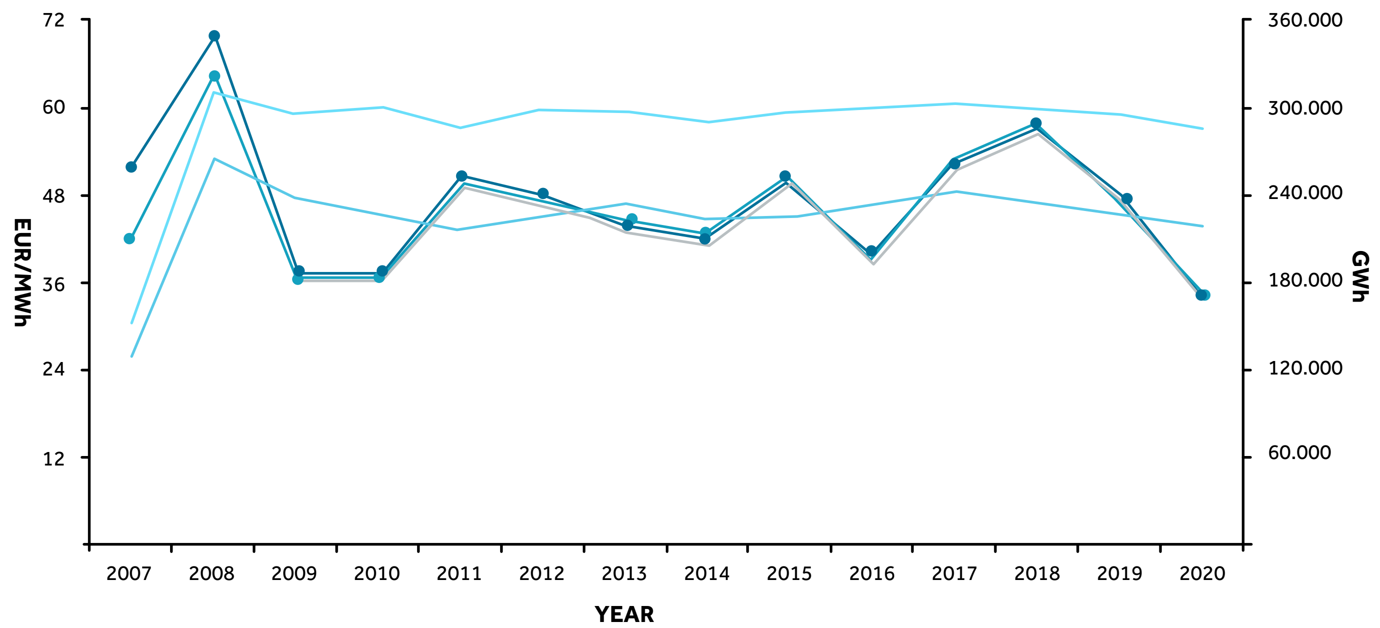


Figure 6 - Evolution of the average annual price from 2007 to 2020[3]. Original from OMIE | Adapted by INESC TEC.

[3] OMIE, 'OMIE (market results download)'. http://www.omie.es/aplicaciones/datosftp/datosftp.jsp (accessed Oct. 31, 2018).

Figure 7 shows the price increase during 2021 from January to September. As can be seen, apart from the decrease in February, prices have been continuously increasing up to now. In fact, a new record price is reached almost each week. For example, the maximum hourly price since the start of the MIBEL in July 2007, and by the time this section was being written, was almost 320 €/MWh, with an average daily price of 289 €/MWh; this took place on October 7, 2021 (see Figure 8), thus reflecting an increase of 271% from March to September.

Day-ahead minimun, average and maximum price
Mibel - 2021

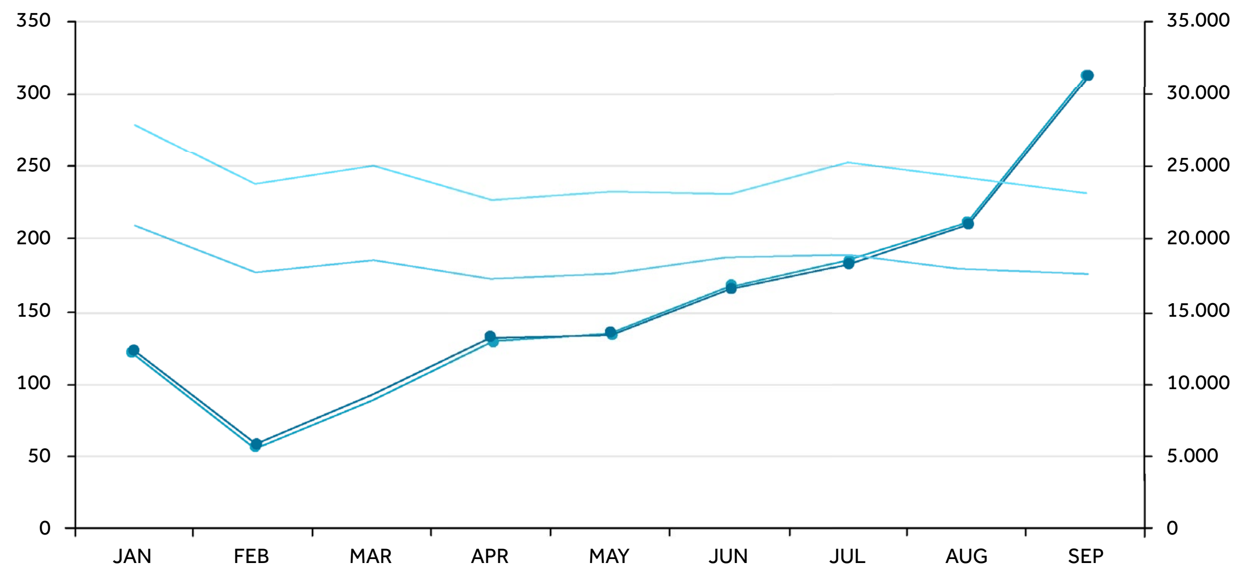


Figure 7 - Evolution of the average monthly price from January to September 2021[3]. Original from OMIE | Adapted by INESC TEC.

Day-ahead hourly prices
07/10/2021

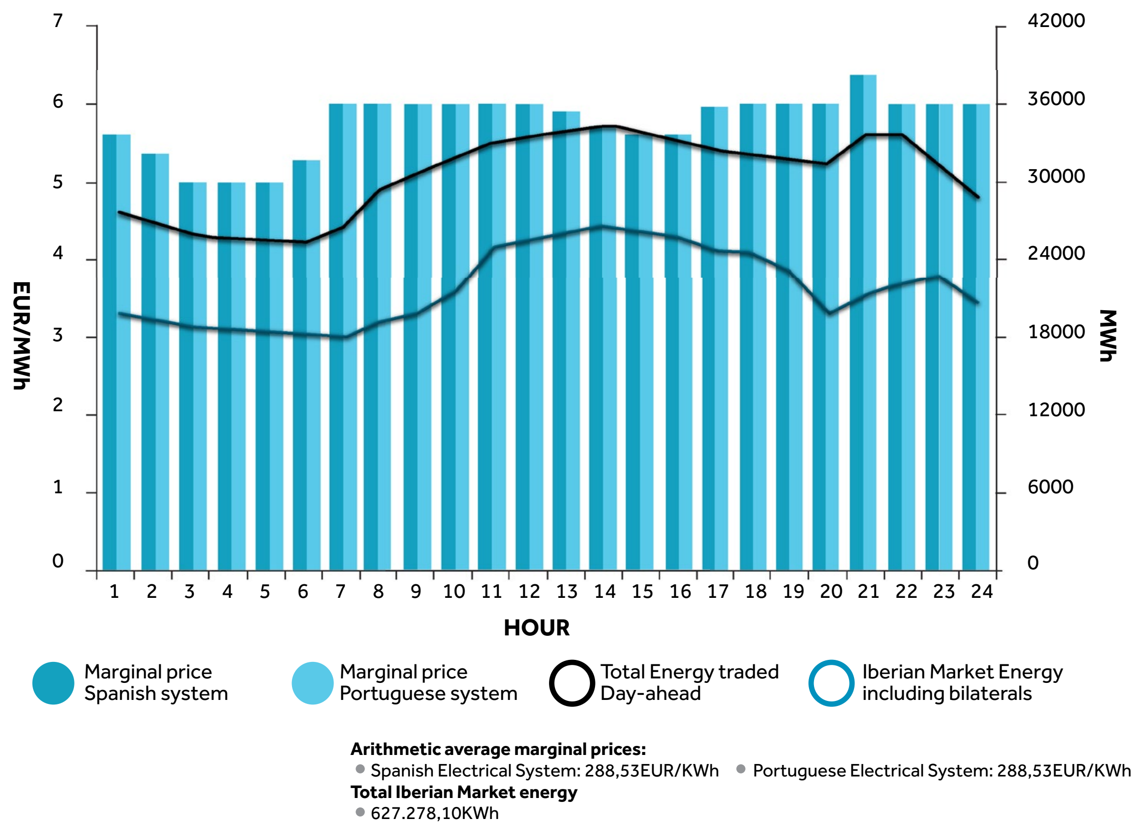


Figure 8 - Hourly prices and traded energy for October 10, 2021[3]. Original from OMIE | Adapted by INESC TEC.

4. Why is this happening?

As in many other situations, there isn't a single reason to explain the recent behaviour of the MIBEL day ahead market clearing prices characterised before. The next paragraphs and figures detail several drivers that contribute to set "the perfect storm" influencing the MIBEL prices (but not only in the Iberian Peninsula, as commented below):

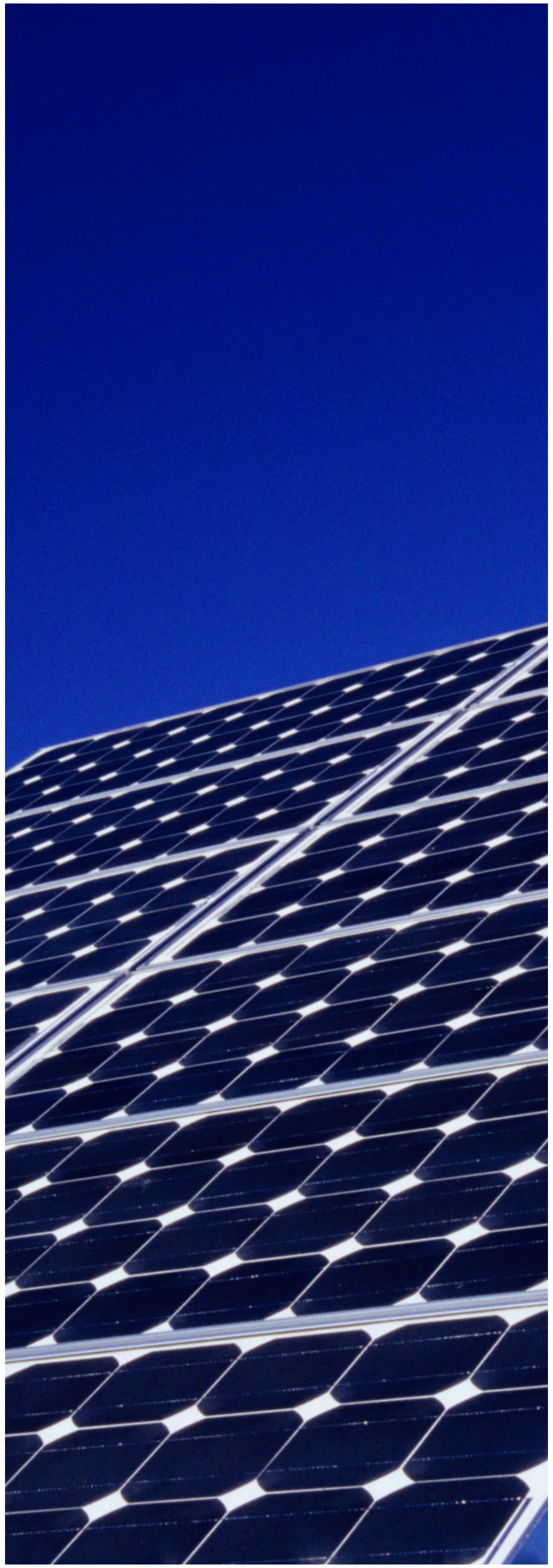
- **Market reform -** a recent MIBEL reform, in July 2021[10], eliminated the limits that constrained the market price to the interval [0 €/MWh; 180 €/MWh], allowing the wider range of [500 €/MWh; 3.000 €/MWh] for the day ahead market, and of [-9.999 €/MWh; 9.999 €/MWh] for the intraday markets. This is a consequence of transposing Article 10 (Technical bidding limits) of EU regulation 2019/943 [11] ato the MIBEL, that states that upper and lower electricity price limits should be avoided, while allowing Market Operators to set, in a coordinated manner, high enough limits if they do not constraint negotiations[12]. In fact, ACER (European Agency for the Cooperation of Energy Regulators) had already established these limits in reference [13]. EAvoiding price limits reflects the belief, shared by the EU Commission, that energy-only markets (where capacity remuneration mechanisms are avoided or very limited) provide better economic conditions to investors in terms of new capacity during hours of scarcity, generation mix at said hours, willingness of the demand to pay to be supplied, etc. They should also allow, under ideal conditions (see section 1), to recover most investments costs. However, in practical terms, prices are very often limited, systems are not adapted, and different capacity remuneration mechanisms with a large impact on generators revenues coexist in the EU. Anyway, and despite not being the main reason behind the current high prices, this reform has certainly allowed to see the current prices going above 180 €/MWh;

[10] 'El "pool" podrá tener precios negativos a partir del próximo 6 de julio'. https://elperiodicodelaenergia.com/el-pool-podra-tener-precios-negativos-a-partir-del-proximo-6-de-julio/ (accessed Oct. 13, 2021).

[11] *Regulation (EU) 2019/943 of the European Parliament and of the Council of 5 June 2019 on the internal market for electricity (Text with EEA relevance.)*, vol. 158. 2019. Accessed: Oct. 25, 2020. [Online]. Available: http://data.europa.eu/eli/reg/2019/943/oj/eng

[12] Comisión Nacional de los Mercados y la Competencia, *BOE 61443, 20/05/2021 - Resolución de 6 de mayo de 2021, de la Comisión Nacional de los Mercados y la Competencia, por la que se aprueban las reglas de funcionamiento de los mercados diario e intradiario de energía eléctrica para su adaptación de los límites de oferta a los límites de casación europeos.* 2021. Accessed: Oct. 21, 2021. [Online]. Available: https://www.omie.es/sites/default/files/2021-05/reglas_omie_boe-a-2021-8362.pdf

[13] ACER, *Decistion of the Agency for the Cooperation of Energy Regulators No 04/2017. 14 novemeber 2017*. Accessed: Oct. 21, 2021. [Online]. Available: https://documents.acer.europa.eu/Official_documents/Acts_of_the_Agency/Individual%20decisions/ACER%20Decision%2004-2017%20on%20NEMOs%20HMMCP%20for%20single%20day-ahead%20coupling.pdf



- **Demand increase -** In Portugal, the demand decreased by 3,0% from 2019 to 2020 (from 50,3 TWh to 48,8 TWh in 2020)[4]. Due to the economic recovery that started in 2021, more intense from the second quarter of 2021 onwards, the demand is now increasing. If we compare the values for the first semester of 2019, 2020 and 2021 (24,0 TWh, 23,3 TWh and 24,9 TWh) we can conclude that, in 2021, the demand increased about 7,0% when compared to 2020, and 3,7% when compared to 2019. This reflects the expected increase of the GDP for 2021 (4,8% according to recent projections) and the expected GDP increase for 2022 (5,5% as announced recently) and suggests that the pre-pandemic economic activity level will be reached in the first months of 2022. From the MIBEL day ahead market point of view, more demand means that more expensive units will need to be cleared to supply the demand, setting the price to higher values;

- **Decommissioning of coal units -** as mentioned in Section 2, Portugal and Spain started a movement to decommission very polluting coal thermal units[14]. Table I indicates that the coal installed capacity already decreased from 1756 MW in 2010 to 576 MW in Portugal (and this value will likely come to zero, as the Pego coal station is planned to shut down in 2022), and from 11380 MW (2010) to 5733 MW (2020) in Spain. This reduction is explained by the need to buy CO2 emission licences for these units, licences that are also seeing their prices increasing, and by a reduction of the gas price compared to coal during 2019, leaving coal plants out of the market, and accelerating their decommissioning plans.

[4] 'REN - Eletricidade'. https://www.ren.pt/pt-PT/o_que_fazemos/eletricidade (accessed Oct. 13, 2021).

[14] A. R. de Oliveira et al., 'Joint analysis of the Portuguese and Spanish NECP for 2021-2030', in 2020 17th International Conference on the European Energy Market (EEM), Stockholm, Sweden, Sep. 2020, pp. 1–6. doi: 10/gjq3f3.

- As a result, less polluting natural gas units became less costly and more competitive than coal power stations. Despite this beneficial environmental impact, from the strict point of view of the generation system, these changes determined a less diversified generation mix or, in other words, a generation system more dependent on the natural gas and its price evolution. As the price of natural gas started to increase in the international markets, this larger dependency on this primary resource had a direct impact on the electricity market prices. This move is not restricted to Portugal and Spain since several other EU countries also started to shut down more polluting coal power stations, thus becoming more dependent on natural gas units. It should be noticed that the marginal cost of the combined cycle units can be estimated roughly as the gas price divided by the efficiency (about 50%) plus the CO2 emissions cost by the emission factor (about 0,4). This means that, when these technologies are marginal or the dispatchable hydro considers the opportunity cost of substituting combined cycle units, the price reaches this marginal cost. With gas prices approaching 120 €/MWh and CO2 emissions above 60 €/ton, electricity prices rise to 260 €/MWh;

- **Increase of the natural gas prices -** cas detailed in the previous point, over recent years, the Portuguese and the Spanish generation systems became more dependent on the supply of natural gas. Its price remained at a low level along 2020 and started to increase by the Autumn of 2020, as seen in Figure 9, showing the evolution of the price of future gas contracts in the Dutch TTF market, and its dramatic increase during the last months. This increase is caused by several factors: gas demand increase caused by the electricity demand surge influenced by the post-pandemic economic recovery in China and in other emergent countries; the EU reservoirs reaching lower levels, and China's strategy to buy extra volumes of natural gas for storage, as a way to deal with potential scarcity periods. In addition, there are also strategic problems in terms of natural gas supply in the EU, since several countries aim to reduce their dependency on the supplies from Russia and, while Germany and Russia are now connected by a new pipeline -Nord Stream 2, established in the Baltic Sea - that links the Saint Petersburg Russian area to Greifswald, in the northeast cost of Germany. Early this month, it was announced that this pipeline would start being filled for tests, and that the German government perceives it as an additional gas supply point that could contribute to a decrease of the natural gas prices in Europe in the medium to long term;

Dutch TTF natural gas prices

On october 5, the benchmark European gas futures contract hit a record high of over €107 per MWh

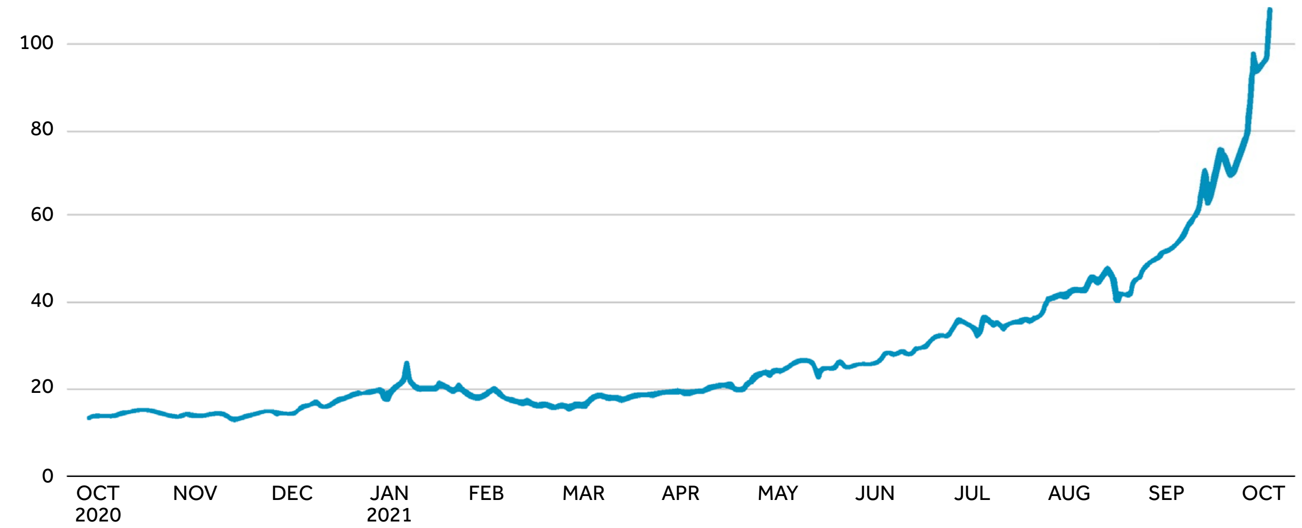


Figure 9 - Evolution of the price of the natural gas TTF future contracts[15]. Original from OMIE | Adapted by INESC TEC.

- **Increase of the price of the CO_2 emission licences -** the CO_2 emission licence mechanism was designed at the EU level to reduce greenhouse gas emissions caused by activities responsible for 45% of EU emission volume, considering the reference year of 1990. This mechanism sets the global amount of CO_2 emission licences, allocating these licences to the EU countries and to several economic activities. Moreover, these licences can be traded, meaning that an agent that manages to reduce its emissions below the allowed level can sell its surplus licences to other agents. In addition, this mechanism included a yearly reduction factor of 1,74% in the period of 2013-2020, increasing to 2,2% per year from 2021 to 2030. Given the progressive reduction of existing licences, their price started to increase in 2018, as seen in Figure 10, with the values in €/ton of CO_2 emissions. In addition to the licences' reduction, which by itself will increase CO_2 prices, in 2018 - and in order to increase the CO_2 price to promote the decarbonisation process -, the EU[12] permitiu que allowed negotiating the CO2 emissions as financial instruments, so that investment banks started to play in the market, contributing to the price increment. The Brexit process is also having some impact on the CO_2 prices, since UK companies must abandon the EU emissions trading system, by selling their emissions rights and buying new ones in their own new market. The overall CO_2 price increment is more noticeable from the mid 2020 onwards, and it is also caused by the increase of the economic activity along 2021. In September 2021, its price reached 60 €/ton, i.e., an increase of about 55 €/ton regarding the values of 2013/14, and several reports indicate that this value will potentially increase to more than 90 €/ton in 2030;

[15] 'Europe's gas prices just hit yet another record', Fortune. https://fortune.com/2021/10/05/gas-price-crisis-europe-energy/ (accessed Oct. 11, 2021).

- On the other hand, the Council of Regulators of Portugal and Spain published a study on the impact of the CO2 licence prices on the electricity market price [16]. This report indicates that for each Euro of CO2 price increase there is an impact of 0,5 to 0,6 €/MWh on the electricity market price. This means that regarding 2013/2014, given that the CO2 licence price increased from about 5 €/ton to 60 €/ton, that is a 55 €/ton rise, the direct market price impact ranged from 27.5 to 33.0 €/MWh. In recent years, and with the more intense use of natural gas power stations, this impact will most likely increase.

CO_2 emissions price (€/ton)

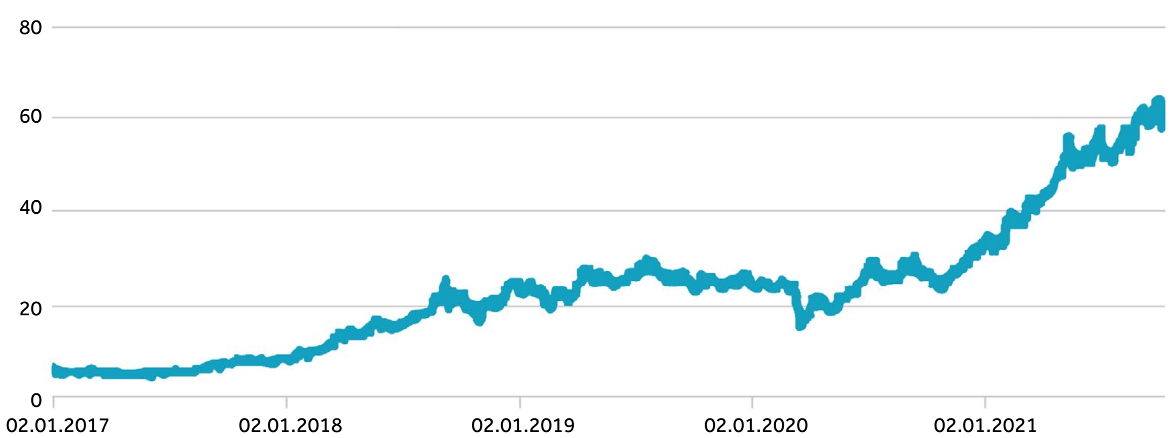


Figure 10 - : Evolution of the price of the CO_2 licenses in €/ton in the EU[17]. Original from OMIE | Adapted by INESC TEC.

[16] Conselho de Reguladores do MIBEL, 'Estudo sobre o mercado de licenças de emissão de CO2', Jul. 2020. Accessed: Oct. 11, 2021. [Online]. Available: https://www.mibel.com/wp-content/uploads/2021/06/Estudo_MIBEL_Mercado_CO2_vers_PT.

[17] 'Precios CO2 - Sendeco2'. https://www.sendeco2.com/es/precios-co2 (accessed Oct. 31, 2018).

- **EU electricity prices -** as can be seen in Figure 11, the high electricity prices are not a local MIBEL problem, but an issue that affects most EU countries, although with different impact. While northern countries are facing lower prices than other EU countries, thanks to their large renewable generation share (that includes a large amount of hydro generation), their prices are still much higher than before. In Norway, for example, prices in September were five times higher than one year ago[18], and their currently low hydro reservoirs may still contribute to the EU prices increase over the upcoming months.

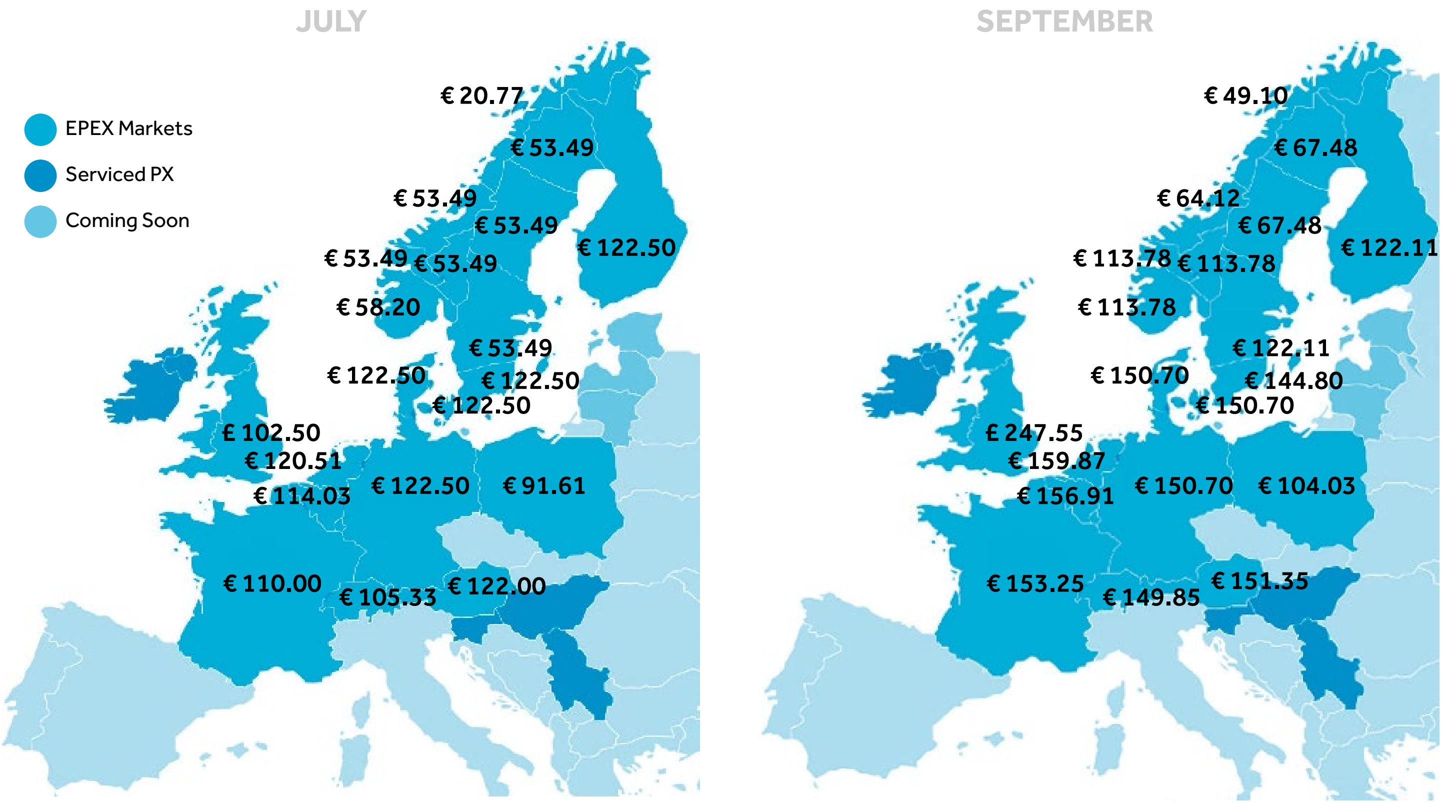


Figura 11 - EPEX market prices a) July 2, at 8:00 (left) and b) September 19-20 (right)[19] [20] | Adapted by INESC TEC.t

[18] 'Europe's Power Crisis Moves North as Water Shortage Persists', Bloomberg.com, Oct. 03, 2021. Accessed: Oct. 12, 2021. [Online]. Available: https://www.bloomberg.com/news/articles/2021-10-03/europe-s-power-crisis-is-moving-north-as-water-shortage-worsens

[19] Pánico en los mercados energéticos europeos: precios récord de gas y CO2 empujan a la electricidad a niveles históricos'. https://elperiodicodelaenergia.com/panico-en-los-mercados-energeticos-europeos-precios-record-de-gas-y-co2-empujan-a-la-electricidad-a-niveles-historicos/ (accessed Oct. 11, 2021).

[20] B. Times <info@bylinetimes.com> (https://bylinetimes.com/), 'The Brexit Tax: How Boris Johnson Broke his Promise on Energy Prices', Byline Times, Sep. 20, 2021. 2 (accessed Oct. 11, 2021).

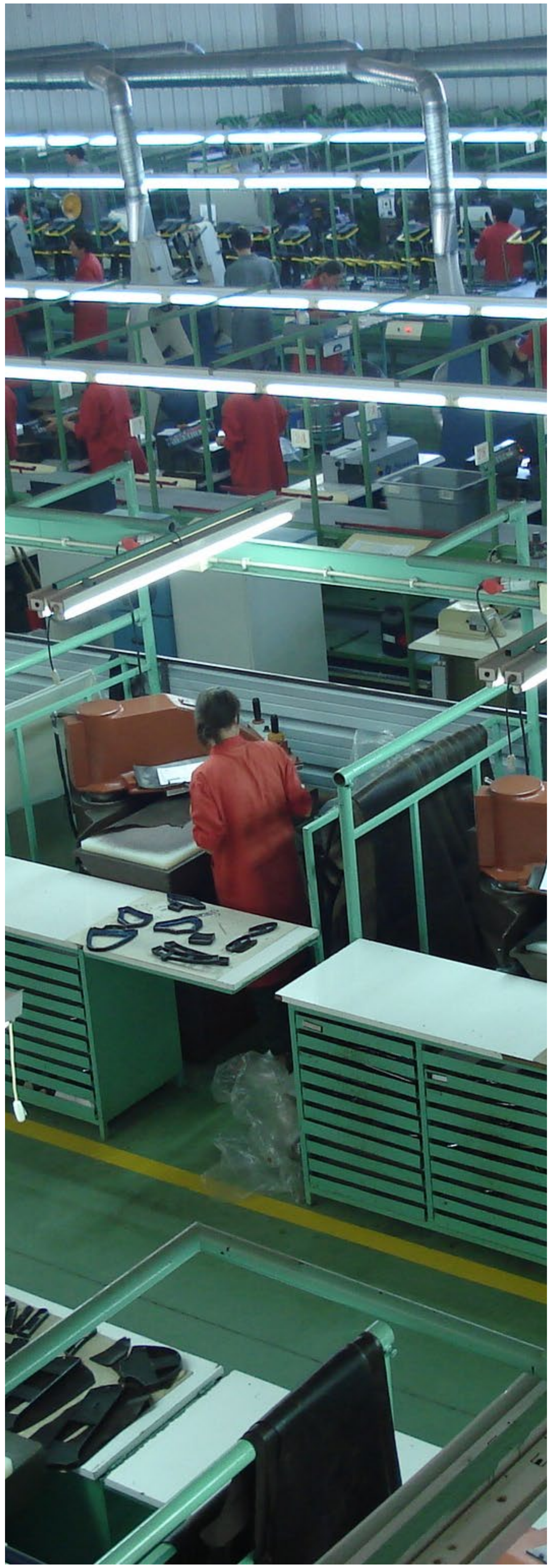
5. Consequences and future perspectives

High energy prices have a deep impact on residential, industrial and services economies. Apart from lowering the purchasing power of residential consumers that rely mostly on gas and electricity, it also leads to several consequences that affect the industrial and services sectors. Several electricity-retailing companies are facing very complex situations when their contracts are not indexed to the electricity prices and cannot be renegotiated, and some are already entering or facing very high risk of bankruptcy [21] [22]. Electro-intensive industries, also exposed to high raw material prices, are even planning, in some cases, to stop their production temporally [23].

[21] 'Failing energy companies: latest updates', Which? News, Oct. 04, 2021. https://www.which.co.uk/news/2021/10/failing-energy-companies-latest-updates/ (accessed Oct. 12, 2021).

[22] D. Cordero, 'Competencia alerta sobre posibles quiebras de comercializadoras eléctricas por el alza tarifaria', El País, Sep. 28, 2021. https://elpais.com/economia/2021-09-28/competencia-alerta-sobre-posibles-quiebras-de-comercializadoras-electricas-por-el-alza-tarifaria.html (accessed Oct. 12, 2021).

[23] J. Vadillo, 'Sidenor, la primera industria que para 20 días por el "desorbitado" precio de la luz', Cinco Días, Oct. 12, 2021. https://cincodias.elpais.com/cincodias/2021/10/11/companias/1633947378_745739.html (accessed Oct. 12, 2021).



Future perspectives are difficult to foresee, since they are the combination of complex and interrelated factors difficult to assess; but some sources believe that prices will keep increasing over the following months [24], namely during winter. For the short term, the combination of low hydro reservoirs and the low European gas storage levels will increase the dependency on natural gas, and gas prices are still expected to rise considering the worldwide demand and low reserves. A more coordinated negotiation of the EU with gas suppliers could decrease its price in the long run, but this generally implies larger contracted volumes, which could lead to unfair future obligations for those countries with large renewable energy potential under development, like the MIBEL countries. The decommissioning of nuclear and coal plants, and the increasing electrification (for instance associated with electric mobility) will also reduce the supply and increase the demand, and the increase of natural gas usage will have to be balanced with an important increase of renewable generation. Finally, EU emissions rights prices are not expected to decrease, since they are part of the EU strategy towards decarbonisation.

Market reforms are under debate, but many believe that uniform pricing should be maintained, since it provides the right economic signals to the market agents. Hence, the measures should focus on increasing renewable generation capacity and energy storage and reserves, including green hydrogen, to decrease the dependence on fossil fuels, which implies further developments of long term and capacity markets, reducing electricity taxes, reducing CO_2 speculation and providing direct support to consumers [25] [26]. In some countries, like Spain, measures include, among others, the infra-marginal generators' obligation to stop producing CO_2 (nuclear, hydro, and some wind farms with market-indexed contracts), while giving back the extra income they get thanks to the high CO_2 and gas prices, as well as the uniform pricing mechanism already described. However, there are many criticism surrounding this measure, since it introduces, yet again, a new regulatory uncertainty, due to its potential lack of legal soundness, while, in some cases, making generation companies sell the energy to suppliers at fix or non-market indexed prices, which could prevent them from recovering costs[27].

[24] elEconomista.es, 'La inflación se descontrola: el precio de la electricidad se mantendrá caro hasta 2024'. https://www.eleconomista.es/empresas-finanzas/noticias/11415636/10/21/La-inflacion-se-descontrola-el-precio-de-la-electricidad-se-mantendra-caro-hasta-2024.html (accessed Oct. 12, 2021).

[25] 'MEPs debate EU solutions to rising energy prices | News | European Parliament', Oct. 06, 2021. https://www.europarl.europa.eu/news/en/headlines/economy/20210930STO13941/meps-debate-eu-solutions-to-rising-energy-prices (accessed Oct. 12, 2021).

[26] 'EU prepares "toolbox" of measures to tackle energy price spike', www.euractiv.com, Sep. 23, 2021. https://www.euractiv.com/section/energy/news/eu-prepares-toolbox-of-measures-to-tackle-energy-price-spike/ (accessed Oct. 12, 2021).

[27] M. Á. Noceda, 'Las grandes eléctricas advierten de que el recorte de la retribución llevará a muchas centrales a pérdidas', El País, Sep. 21, 2021. https://elpais.com/economia/2021-09-21/el-precio-de-la-electricidad-vuelve-a-dispararse-y-superara-los-175-euros-mwh-este-miercoles.html (accessed Oct. 12, 2021).

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