Universidad Politécnica de Madrid
Escuela Técnica Superior de Ingenieros de Telecomunicación

Contribution to energy consumption modelling and forecast in next generation access networks

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Rafael Coomonte Belmonte
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Contribution to energy consumption modelling and forecast in next generation access networks

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Author:
Rafael Coomonte Belmonte
Ingeniero de Telecomunicaciones
Universidad Politécnica de Madrid

Directores:
Claudio Feijóo González
Doctor ingeniero de Telecomunicaciones
Profesor Titular del Dpto. de Señales, Sistemas y Radiocomunicaciones
Universidad Politécnica de Madrid
José Luis Gómez Barroso
Doctor ingeniero de Telecomunicaciones
Profesor del Departamento de Economía Aplicada e Historia Económica
Universidad Nacional de Educación a Distancia

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Calificación

El Presidente **Los vocales**

El Secretario

“Yo soy una parte de todo aquello
que he encontrado en mi camino”

Alfred Tennyson

A Carol que ha andado a mi lado este camino.
Y a Carla que pronto estará junto a nosotros para andarlo.

FOREWORD

Cuando uno empieza a escribir esta parte es porque el trabajo ya está hecho, puesto negro sobre blanco y empiezas a acordarte de todo aquello que te acompañó durante todo el tiempo que dedicaste a hacerlo.

Tiempo que no siempre fue fácil pero que contó con muchos apoyos y gente que estuvo cerca en los momentos en los que se hacía más difícil. Gente que incluso sin quererlo te ayudó a comprender cosas que quizás solo no habrías entendido.

No puedo dejar pasar la oportunidad de agradecerles a todas esas personas el haberme ayudado a conseguir este objetivo.

A los que pensaron que yo sería capaz de conseguir ser Doctor. A Vicente Ortega que me dio la primera oportunidad de emprender el doctorado, a través de la Cátedra Isdefe, donde también tuve la suerte de contar con Consuelo que estuvo siempre a mi lado apoyándome. A Andrés Gavira, que como tutor del proyecto STAREBEI del Banco Europeo de Inversiones, ayudó a que esta tesis se hiciera realidad. Y sobre todo a Claudio Feijóo y a Sergio Ramos, que siempre creyeron que llegaría hasta el final incluso cuando a mí más me costaba hacerlo.

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A todos aquellos que viven mí día a día, que no son pocos, y que más que nombrarlos aquí prefiero tenerlos siempre en mi cabeza, porque hacen que este camino a veces difícil merezca siempre la pena caminarlo.

Y sobre todo a Carol porque después de este primer parto que es esta tesis que lo suyo ha costado, vamos a defender juntos otra que será la más importante de nuestras vidas.

ABSTRACT

The contribution from the information and communications technology (ICT) sector to global energy consumption has considerably increased in the last decade, along with its growing relevance to the overall economy. This trend will continue due to the seemingly ever greater use of these technologies. One of the primary ingredients is broadband data traffic generated by the usage of telecommunication networks. In fact, as a response to user demands, the telecom industry is initiating the deployment of next generation networks (NGNs). However, energy consumption is mostly absent from the debate on these deployments, in spite of the potential impact this could have on both expenses and sustainability.

This work addresses the forecast of energy consumption in the access part of NGNs by modelling the combined effect of the deployment of different ultra-broadband technologies, the evolution of traffic per user, and the energy consumption in each of the network and user devices. Conclusions are presented on the levels of energy consumption, their cost, and the impact of different network design parameters. The effect of technological developments, techno-economic and policy decisions on energy consumption is highlighted. Practical figures and comparisons across technologies are provided. For calculations, the work considers in detail the case of Spain, although the model and conclusions can be easily extended to similar countries.

RESUMEN

La contribución del sector de las tecnologías de la información y las comunicaciones (TICs) al consumo de energía a nivel global se ha visto incrementada considerablemente en la última década al mismo tiempo que su relevancia dentro de la economía global. Se prevé que esta tendencia continúe debido al uso cada vez más intensivo de estas tecnologías. Una de las principales causas es el tráfico de datos de banda ancha generado por el uso de las redes de telecomunicaciones. De hecho como respuesta a esta demanda de recursos por parte de los usuarios, de la industria de las telecomunicaciones está iniciando el despliegue de las redes de nueva generación. En cualquier caso, el consumo de energía es un factor generalmente ausente del debate sobre el despliegue de estas tecnologías, a pesar de la posible repercusión que pueda llegar a tener en los costes y la sostenibilidad de estos proyectos.

A lo largo de este trabajo se desarrollan modelos para evaluar el consumo energético de las redes de acceso de nueva generación (NGAN). Estos servirán tanto para llevar a cabo cálculos en un escenario global estático, como en cualquiera otro que determine la potencial evolución de la red de acceso a lo largo de su despliegue. Estos modelos combinan tres factores: la penetración prospectiva de cada una de las tecnologías de banda ancha analizadas, el tráfico generado por usuario y su futura evolución, y el perfil de consumo de energía de cada uno de los dispositivos de red desplegados.

Tras evaluar los resultados derivados de la aplicación de los modelos en el caso demográfico específico de España, se obtienen conclusiones acerca de las diferencias tecnológicas en cuanto al consumo energético, sus implicaciones económicas, y la sensibilidad de los cálculos atendiendo a posibles modificaciones en los valores de referencia de diferentes parámetros de diseño. Se destaca por tanto el efecto en el consumo energético de los desarrollos tecnológicos, tecno-económicos, y de las decisiones en el ámbito regulatorio. Aunque como se ha dicho, se ha ejemplificado el cálculo para un caso particular, tanto los modelos como las conclusiones extraídas se pueden extrapolar a otros países similares.

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1. INTRODUCTION

1.1. BACKGROUND – NEXT GENERATION NETWORKS AND ECONOMIC GROWTH

The rise of what has been called the knowledge economy or new economy has reinforced the role of telecommunications as a strategic investment. The consensus regarding the importance of telecommunications has changed the reasoning at play. It no longer includes the existence of an adequate infrastructure as a factor affecting regional development. Instead, its absence is considered a sign of underdevelopment. As a result, governments pay particular attention to telecommunications. Almost all countries, including a good number of the less developed ones, have launched their own proposals for adapting their economies to the new socioeconomic paradigm that is taking shape. Any document related to a plan aimed at promoting the information society tries to prove the "importance of broadband" and the problems resulting from the existence of digital divides.

As an example, the Communication from the Commission entitled "Bridging the broadband gap" (EC, 2006) offers a categorical argument: widespread broadband access is a key condition for the development of modern economies and is an important aspect of the Lisbon Agenda. Additionally, it includes a section with exactly that name ("why broadband matters"), in which it develops the arguments in further detail:

> *"The impact of broadband is just beginning to be felt. The precise impact has been difficult to measure. It is, however, clear that the ability to communicate information at high speeds and through various platforms is key to the development of new goods and services. Broadband enables new applications and enhances the capacity of existing ones. It stimulates economic growth through the creation of new services and the opening up of new investment and jobs opportunities. But broadband also enhances the productivity of many existing processes, leading to better wages and better returns on investment".*

Certainly, as declared, the impact is not easy to assess, although the academic scope has been trying to do so for decades. Among the pioneers, Saunders, Warford, and Wellenius (1983) established the relationship between communications and the growth of the services industry, which in turn was correlated with that of the gross national prodcut (GNP). This correlation between economic activity level and investments in telecommunications infrastructures was described by Cronin, Parker, Colleran, and Gold (1991), Dholakia and Harlam (1994) or, more recently, Röller and Waverman (2001), using econometric techniques. However, are telecommunications the cause or the consequence of the level of development? There is a bi-directional relationship; the investment in telecommunications is a reliable predictor of the subsequent economic activity level; the converse is also true (Cronin, Parker, Colleran, & Gold, 1993).

Regarding the mechanism used by telecommunications to positively influence the economy, productivity improvements and efficiency growth in markets due to the agents' being able to more swiftly answer the market signals are initially stated as basic factors (Madden & Savage, 1998; Wellenius, 1984). The list can be further detailed: less production costs, better location decisions, increased flexibility, reduced storage (and resulting capital cost) with the just-in-time production methods and an increase in competition, among others, can be included (Cave, Milne, & Scanlan, 1994). As regards how it affects employment, Hansen, Cleevely, Wadsworth, Bailey, and Bakewell (1990) found that, in six European rural areas, the impact on employment of the investment in telecommunications was between 2.2 and 5.2 times greater during the first year than at the time of the original investment.

As stated before, the relationship seems clearer today in the presence of what has been called the knowledge economy, or the new economy. Telecommunications, converging with other industries towards the integration of the ICTs, act as an engine of the economy and as a source of productivity and employment and thus are universally considered as a strategic investment, see among may others: OECD (2003), Jalava and Pohjola (2007); Timmer and Van Ark (2005); Venturini (2009). Other works refers specifically to the impact of broadband (Koutroumpis, 2009).

In line with the high expectations regarding their role as a development driver, public administrations have jumped in to encourage the deployment of Next Generation Networks (NGNs). But the debate around clearly establishing the market limits is maybe the one on the table preventing these deployments form evolving faster. Although some claim that this innovation is a solution to a problem that does not exist, others estate that while excessive at the time, it is called to be enormously beneficial in the future. While some studies (Ford, Grossman, & Handler, 2009) agree on the beneficial effects for emerging countries some questions around the effects of investing in the deployment of these advanced infrastructures in countries where solid ones already exist have arisen.

The economic assessment by Pellegrino and Klemann (2012) shows that the benefits of an upgrade from conventional Internet access to ultra-broadband (UBB)[1] are threefold: i) increase economic prosperity; ii) create jobs; and iii) improve the public's welfare by, for example, providing better access to healthcare and education. Quantitative measurements of the effects of UBB deployments are shown in Table 1.1.

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[1] Ultra-broadband (UBB) refers to ultra-high-speed broadband transmission supporting download speeds of 50 Mbps and above (potentially 100 Mbps and higher), providing high-speed symmetrical low-latency capacity, and capable of handling next-generation applications. UBB requires a Fibre-optic access network—Fibre to the business (FTTB) or Fiber to the Home (FTTH) deployment.

Table 1.1 – Effects of ultra-broadband on GDP, employment, and public good. Source: (Pellegrino & Klemann, 2012)

Type of effect	*Value*	*Remarks*
GDP Growth		Direct effects are a result of investment in Fibre access network. Indirect effects are the capacity of the economy to promote innovation, offering new services and enabling substantial economic development
Direct	+1.1%	
Indirect	+3.5%	
Employment growth	+1.1%	Overall job creation
Public welfare (as measured by HDI[2]	+14%	The United Nations Development Program Human Development Index (HDI) takes into consideration network effects on welfare key indicators

Besides the benefits declared, many uncertainties darken the pathway of innovations in this field. The need of intensive investment makes it difficult to take any step forward without thoroughly analysing the problem from many different angles.

First, the implication of the diverse actors involved in the process is yet to be determined, and this is mainly driven by the economic implications and the uncertainties on the possible business opportunities derived from the deployments. The debate of whether governments should assist in deploying UBB is almost certain to trigger a hot debate (J. L. Gómez-Barroso & Feijóo, 2010b). Some compared the development of data networks to the realization of the national distribution grid for electricity a century ago[3] (Pellegrino & Klemann, 2012). Believers in a "new digital renaissance" view the new network infrastructure as the enabler of rapid global economic recovery, improved public services and institutions, and increased cultural enrichment in each country.

On the other hand the telecomm operators in charge of implementing the whole deployment are not very eager to rush into the process without some guarantees that ensure the profitability and economic feasibility of their investment. The potential hindrances derived from regulatory conditions, the market openness that oblige to share the number of subscribers among an undetermined number of operators (see Figure 1.1 for a plausible prospective competition scenario in Spain)[4], or the need of deploying the network avoiding any digital gap in zones less economically attractive, are some of the reasons that slow down the innovation process.

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[2] Human Development Index (HDI). A composite measure of achievements in three basic dimensions of human development: a long and healthy life, access to education and a decent standard of living.

[3] EEUU President Barack Obama(September, 2011) http://www.whitehouse.gov/issues/technology , and German Chancellor Angela Merkel (February, 2008) http://www.youtube.com/watch?v=KljB8LIyglQ

[4] Figure retrieved from previous work on the cost of NGAN deployment by C. Feijóo and J.L Gomez-Barroso in 2010.

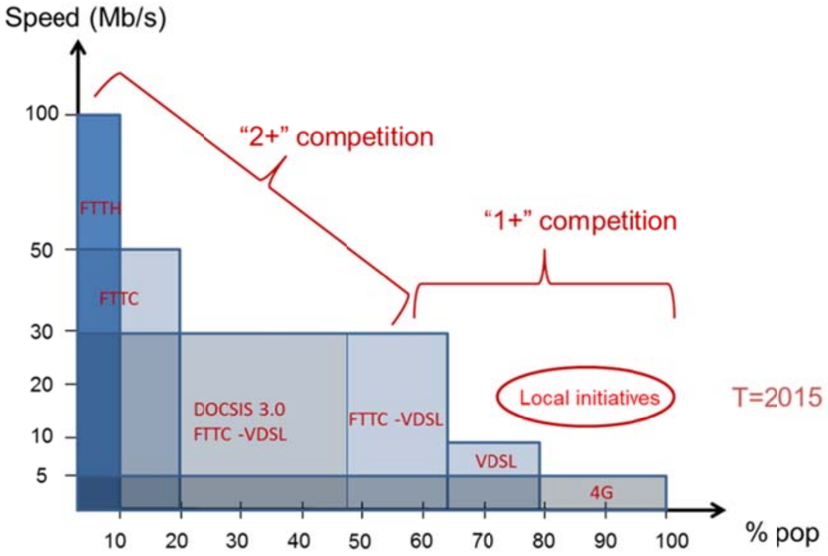

Figure 1.1 – A potential baseline competition scenario for Spain in 2015.

As these two sides are bound to meet, if not in the middle in a place mutually beneficial, many initiatives try to define the frameworks for a public-private partnership (Falch & Henten, 2010; J. L. Gómez-Barroso & Feijóo, 2010a). This together with the definition of potential attractive ultra-broadband services (Feijóo, 2011), that match supply and demand side, could improve significantly the future expectations on the benefits of participating in the "reinvolvement" in infrastructure deployment.

Therefore any measurement regarding the costs involved, positively contribute to the discussion about the suitability of undertaking this type of projects. In this sense energy is a necessary resource that derives in costs that cannot be eluded for proper network operation. At best the level of consumption can be reduced, by integrating smart network management, more efficient technologies and active network devices, or any other strategy that improve the use of resources and enhance the network layout in each scenario. This would also provide an assessment of the sustainability of the infrastructures and the environmental balance derived from the benefits these will also arrange.

The research here described focus precisely in this aspect not always bear in mind along the process of designing these infrastructures, as it has already been stated.

1.2. BACKGROUND – NEXT GENERATION NETWORKS AND SUSTAINABILITY

Many sustainability challenges pervade the planet—so much so that the topic of sustainability is playing an increasingly important role as a factor in everyday socioeconomic decisions. "Green consumption" attitudes and habits are developing as part of more socially conscious behaviour. Businesses are becoming more aware of this trend and are adapting their strategies accordingly. In fact, large multinational corporations (as for instance many telecom operators) are regarded as playing a specific role in sustainable development; their potential for being not only part of the problem but also part of the solution is increasingly recognised (Kolk & van Tulder, 2010). At the same time, citizens are more and more conscious of their role in the building of the society in where they live, and also try to put their two cents in making a more sustainable society. Therefore, energy-saving aspects are becoming a factor to be carefully considered.

Already true today, this won't be but progressively more important in the next years. In these sense reducing energy consumption has become one of the main challenges for most countries. For instance, the European Union member states agreed to reduce greenhouse gas (GHG) emissions levels by 20% of the 1990 levels by 2020 (EC, 2008).

But, do the same "green" rules apply to any market segment? The answer, obviously, is no. First, real or perceived environmental impacts differ across industries; so any consistency in consumption behaviour is difficult to measure. Then again every sector does not rely on the same information sources or decision-making criteria, consider the same options, or focus on the same actors (McDonald, Oates, Thyne, Alevizou, & McMorland, 2009). This leads to the necessity of using different models and adapted criterion allowing separate analysis of each sector.

While the importance of information and communications technologies (ICT) sector has considerably grown along the last decades specially in developed countries (EC, 2001), few studies related to these energy consumption matters have been conducted in the telecommunications field. Røpke (2012) highlights that *"although the integration of ICT in everyday life has considerable environmental impacts, this concern has played a very minor role in the research community studying people's use of ICT"*. The information technologies sector, which is also similar to the telecommunications sector, has also been the subject of considerable activity in the definition of paths and guidelines for adoption of more sustainable practices (Murugesan, 2008), although again, there is a scarcity of quantitative references.

In 2007, ICTs accounted for 2% of total carbon emissions of the industrial sector (Gartner, 2007). However, because of continuing increases in usage, the ICT sector's own emissions are expected to increase to 170% of the 2002 levels by 2020 (GeSI, 2008). This added to the expected risk of increase in energy prices (EC, 2009, 2010c; IEA, 2010), should be more than enough to take the energy subject seriously into consideration in a sector that already requires intensive investments to continue its enhancement and progress.

At the same time, ICT-based applications and services are expected to create energy-saving opportunities, reducing emissions by five times the energy footprint of the sector (GeSI, 2008), although the amount of these savings is being debated (Falch, 2010). Any of these new potential ICT-based opportunities requires UBB networks, cloud computing solutions and the deployment of new devices and sensors. These developments will impact the three major components of the energy consumption due to ICTs: telecommunication networks, data centres and user equipment (Sutherland, 2009). Acknowledging the potential environmental impact of current components and of future innovations in the field, will determine whether newer, more environmentally benign paradigms are developed and are beneficial (Røpke, 2012) and whether these new paradigms replace older, environmentally harmful technology paradigms (Windrum, Ciarli, & Birchenhall, 2009).

The above discussion shows that although environmental matters are far from being a hot topic in today's telecom markets, duly marketed "green strategies" may nonetheless be productive. For a medium- to long-term time horizon, this assertion could be reaffirmed, assuming that concerns for global, social and environmental well-being will increase.

In spite of the evidence of these trends, the impact of energy consumption of the upcoming infrastructures that will provide ultra-broadband access, the NGNs, seems mostly absent from analyses of their deployment and usage. The potential of this infrastructure innovation to make a significant contribution to reducing the carbon footprint of the ICT sector was anticipated (ITU, 2008b) but never thoroughly examined. And this in spite of the fact the many authors predict that broadband may become the most important public utility in the 21st-century economy (Melody, 2007; Røpke, 2012) and calling for research on this topic (Murugesan, 2008). In this regard, broadband has several main effects on energy consumption and its wider adoption would raise energy consumption. But, at the same time, it could change positively, in terms of energy, the processes of production, transport and consumption in many sectors: smart buildings, smart grids, or smart transportation systems among others. This would also have mostly unknown systemic effects related to medium or long-term adaptations of behaviour and economic structures that follow the services provided through broadband infrastructures (Røpke, 2012).

Nevertheless a significant degree of innovation is still required to increase the energy efficiency of telecommunications networks. Therefore as a first step on this process it is necessary to stimulate/promote the study of the energy implications associated with the usage of NGNs and with the development of applications based on NGNs that could help improve the efficient use of energy resources in general. Therefore the necessity of assessing the energy consumed by these infrastructures has been identified and tagged as a first necessary step in order to approach the impact of this major component of the ICT sector.

Some earlier approaches to address the topic of NGNs energy consumption have been presented in the technical literature. Baliga, Ayre, Sorin, Hinton, and Tucker (2008) supplied a simple comparison of energy consumption across fibre-based technologies but did not consider network design, deployment or future evolution. There are also an increasing number of technical papers aimed at very specific aspects of energy efficiency during network operation. For instance, Ajmone Marsan and Meo (2011) on energy saving when sharing wireless infrastructures, and López Vizcaíno, Ye, and Tafur Monroy (2012) on modulation techniques in fibre-based networks.

In any case, most of the approaches encountered along this research try to focus on a single upcoming technology, are just simple approaches to a steady-state static scenario, do not integrate the energy efficiency evolution of the related devices deployed, or do not take into consideration factors such as the singularities of a realistic demographic scenario. The issues here included regarding various technologies network evolution on a real scenario have not been addressed in earlier works, let alone combined in a single comprehensive model.

1.3. OBJECTIVES

The overall purpose of this research is therefore to increase awareness of the energy and sustainability choices involved in ultra-broadband technology usage. Thereby the main objective of this research is to depict a model for energy consumption suitable for telecommunication networks, more specifically for the upcoming technology choices currently being considered for the NGN deployments. Relying on the existing vagueness about what the evolution of this networks and their impact on the energy footprint due to ICTs would be, this work attempts to shed some light on the issue pursuing the achievement of some basic objectives.

The first one is to establish an open framework in terms of the basic required design parameters – both in terms of scope, architectures and departing values – so as to develop the energy consumption model for the selected technologies. While most parameters are common for the different technology choices some are particular of each one. Therefore different calculation process must be developed, attending to the formalities of each deployment, but arriving to common references ultimately allowing comparisons among the various choices available. It must be said that the choice of which access technology to use has traditionally been a matter of deployment costs, re-use of the existing infrastructures and expectations of the needs of users. However, the risk of energy increasing derived from the innovations required in broadband access, lead to the inclusion of this feature in the list of choice factors and to the introduction of the energy perspective in the policy debate on network deployment.

This research only considers the access part of network and the operative part of its full life cycle. There are good reasons to constraint the analysis in these two dimensions. With respect to the access choice, the devices in this part of the network are estimated to consume, on average, 5 times less energy than the devices in the transport part, and almost 9 times less than the devices in the core network (Bolla, Bruschi, Davoli, & Cucchietti, 2011). However, the number of devices in the access part of the network represents 94% of the total number of devices in the full network. Therefore, these two factors combined signify that approximately 70% of total consumption takes place in the access network and that the remaining 30% is distributed in the core and transport layers (Shi, Chowdhury, & Mukherjee, 2013). As a consequence, the analysis of the access part of the network appears more relevant. In addition, it is in the access part where the differences among technologies are significant, whereas the transport and core parts of networks are increasingly similar or shared between technologies. The operative part of the network life cycle is where energy is consumed to provide telecom services; thus, it is more relevant to the decisions of operators, and it accounts for the largest part of a network's environmental impact (Scharnhorst, Hilty, & Jolliet, 2006). In fact, according to available studies, more than 50% of the total environmental impact of a network is associated with the operative part of the network's life cycle. (Malmodin, Oliv, & Bergmark, 2001).

Towards the objective of establishing a new decision criterion for the selection of the suitable technology solution for each scenario, the estimation of the economic impact of energy consumption appears as essential. The cost derived from this consumption can have large implications on the costs of network operation, and could affect the economic viability of the deployment. Energy costs are to be compared with

CAPEX, OPEX and total expenditure per subscriber. This can be done thanks to the sharing of basic concepts, mainly on the network design part, with the process followed in previous research work on investment calculations for this type of networks (Feijóo, Gómez-Barroso, & Ramos, 2011; Feijóo, Gómez-Barroso, Ramos, & Coomonte, 2011).

The basic calculation process derives in a steady outline of the consumption levels in a definite demographic scenario. Nevertheless, additional assumptions are required to attain a dynamic (or evolving) perspective along a specific medium to long term period like the one required for network deployment. This is even more important accounting the incipient stage of these upcoming technologies. Citing Sutherland (2009), *"forecasts for the energy consumption are complicated by the evolution [of telecommunications networks]… none of these processes is well understood or easily predicted"*. Hence, this area remains of high research interest and socio-economic relevance. Therefore some ideas on the potential variation of factors such as the network deployment pace, related adoption rates, data demand of users, or the effects of improvements in both the technology and the energy efficiency of devices, help improving the scope of the starting simple overall model that departs from steady-state static considerations. The research proposed the ten year period from 2011 to 2020 as a temporal framework for network deployment.

While it is not the purpose of this work to prove the contribution of UBB networks to energy efficiency and sustainability, it is argued that it could be a potentially positive move for an operator to bring these issues to the forefront and increase its efforts in achieving higher energy efficiency in the networks' operation. Active and informed clients may reward them with their loyalty, which has been shown to be stronger when customers believe that firms behave ethically (Valenzuela, Mulki, & Jaramillo, 2010). Additionally, it would attract those customers who not only consider functionality and price but also search for products that reflect their self-image and values. Last but not least, given the impact of energy consumption on operators' operating expenses, energy savings would also contribute considerably to profitability.

It must be noted that the energy consumption of the customers' own house equipment is defrayed by the end users and not by the operator deploying the network, and so, these factors are excluded from the energy balance of the network. While network consumption is operator's responsibility, the energy consumed by the devices used to access the UBB services provided rests on the consumer's side. Nevertheless this factor contributes significantly to the overall ICT carbon footprint and should be taken into account to explore its approximate level. The wide variety of equipment solutions that can be found in vendor markets make it difficult to study the contribution of this aspect to the energy consumption model, even in the form of a simple percentage (Bolla et al., 2011). With the purpose of adding a comparison point with this other different major component of ICTs, the consumer's equipment, the research includes also a model for an approximate calculation of the energy consumption of user devices in the Spanish scenario.

It must be emphasized that even though the analysis depart from up-to-date market reference values, the 10-year period analysis introduces a lot of uncertainty on the potential evolution of most of the parameters included in the model. Therefore, significant conclusions derived from this work must be obtained from the addition of a sensitivity analysis, which will also help revealing the most critical aspects regarding network design, economic considerations and/or deployment strategy related to energy consumption.

To sum up, the overall purpose of the complete model here presented is contributing to a constructive and open discussion on the benefits of deploying UBB networks from an energy efficiency point of view.

1.4. STRUCTURE

A broad range of elements must be considered in calculating energy consumption in NGAN networks. The objective already described of developing a comprehensive model is approached following the different stages shown in Figure 1.2.

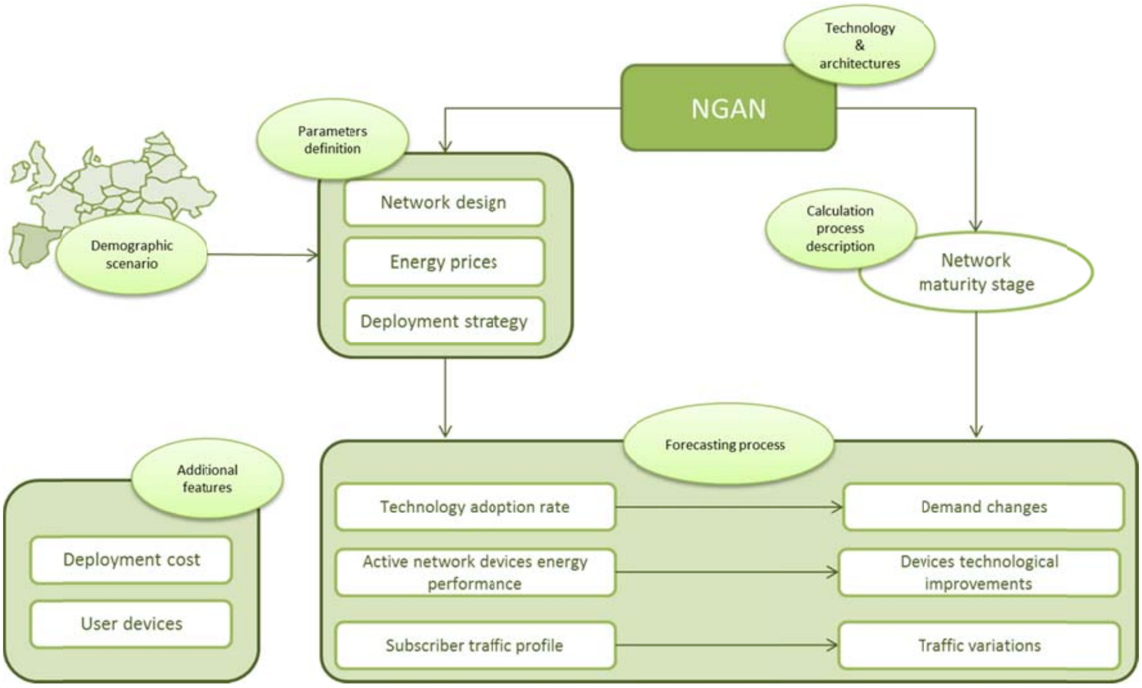

Figure 1.2 – Energy model performance description

The baseline scenario depart in section 2 from a description of the set of technologies selected and their general architectures, depicting in detail the access portion of the network. This allows for a definition of the network basic deployment units suitable for each case, as well as the required active devices for a proper delivery of the UBB services.

Section 3 starts with a brief introduction to the current state of the broadband market in Spain. It then entails a description of how a general demographic scenario is managed in this specific model and then particularized in the selected case of Spain as a socio-economic case. Acknowledging the particularities of the scenario helps in defining the profile of subscribers allocated in each division of the demographic setting.

While the demographic details are essential for the network design in the complete overall scenario, other parameters are equally necessary for the design of the capacity features of the basic deployment units. These details together with coverage and quality objectives, determine the number and type of the active devices required in the network. Therefore, the energy related variables and the energy prices, as well as their reference values are discussed in section 4, with careful consideration of the access network design parameters, encompassing also the deployment strategy that utterly determine the coverage targets disposed by the operator in charge of the deployment.

This last factor would not be necessary in a static scenario, such as the one studied in the first phase of the research. Then, only a yearly assessment attending to specific adoption rates and other steady-state static conditions was performed. That allows obtaining a general perspective of the level of energy consumed along a year of usage of the network when it operates fully deployed, in its maturity stage or in any other selected adoption level proposed. To perform this annual energy consumption valuation level, Section 5 thoroughly describes the full calculation procedure regardless of the specific values of each parameter required.

Anyway the initial model evolves towards assessing the evolution over time of energy consumption levels along the deployment period proposed. For this purposes it is essential to analyse the evolution of the parameters defined in the model, in order to cope with the variation in the access network needs according to them. Although most parameters involved evolve –are evolving- notoriously over time, and beside the fact that they may be included in the calculation process and in the sensitivity analysis, they are not directly used in the forecasting exercise performed also in section 5, beyond pure evolution assumptions based on studies and researches on the field. Others just do not have direct implications in the energy assessment, as for instance the energy prices evolution that reflects only in its related cost. As a consequence of these changes in the reference value of the parameters used, the levels of energy consumption in a broadband network display a significant change along any future timeframe.

The required variations may be caused by a combination of many different factors. Energy consumption of network devices varies as suppliers and operators grow conscious of the economic and societal implications of energy consumption. Users' expectations and demand parameters change as new services and applications are available. The architecture and deployment of the network goes in pace with broadband penetration. Therefore, the research offers a middle-term projection—a baseline—of energy consumption based on modelling three main elements: (i) the consumption profiles of the diverse active devices in the network architecture, (ii) the users' data traffic patterns, which affect the network design and deployment, and (iii) the penetration of each UBB technology using Spanish actual market data. In this process, three different methodologies are combined to obtain this baseline for forecasting: the technological perspective for the consumption of active devices, a techno-economic scenario to construct data traffic patterns, and growth curves for mobile technology penetration.

After completing the description of the energy consumption model, the next sections (section 6 and 7) present additional features to define a framework for comparisons of the results derived from the performance of the model in the spatial and temporal scenario selected. A brief description of the process followed to calculate deployment costs is described. This allows comparisons of energy consumption costs with that required to deploy and maintain the access network section. Next part describes the framework for calculation on the energy consumed by the user devices. It is thus feasible to contrast the level of consumption of two of the three major ICT components.

Many results are presented in section 8, detailing first particular technology consumption profiles and then using the figures to compare technologies or to achieve other comparisons as the ones stated in the previous paragraph between the energy consumption and the additional features described. Also a thorough sensitivity analysis is performed with the

The final section of this work offers some conclusions and implications drawn from of the analysis of the results, covering also some suggestions to continue delving deeper in this research line in aspects that are not covered along the process.

2. NGAN BASIC CONCEPTS

2.1. NEXT GENERATION NETWORKS (NGNS)

The so-called Next Generation Networks (NGN) will become – in the short to middle term - the supporting infrastructure of ubiquitous broadband. They are defined by the International Telecommunications Union (ITU)[5] as "a packet-based network, able to provide services (including Telecommunication Services), to make use of multiple broadband quality of service (QoS) enabled transport technologies and in which service-related functions are independent from underlying transport-related technologies". It offers unrestricted access by users to different service providers, and supports generalized mobility which will allow consistent and ubiquitous provision of services to users.

These upcoming infrastructures are multi-service networks, running over Internet Protocol (IP)-based networks, complemented by flexible service platforms and management systems, offering access to different application and service providers and supporting generalized mobility which will allow consistent and ubiquitous provision of services to users. These technologies will encourage a renewed electronic communication structure where opportunities lie in the provision of ubiquitous broadband connectivity, novel applications, appealing contents and the general support to the sustainable development of all the economic sectors. From their deployment it is – much – expected a wealth of innovations, jobs creation and economic growth.

The uncertainties surrounding the evolution of NGNs are influenced by relatively unknown technology roadmaps, possibly some doubts about the implementation of the regulatory scenario, as well as, especially, the economic uncertainties about the return on investments: "While most people agree that the future of communications networks is based on NGN concepts, less is known about the financial impact of this transformation. In today's competitive environment, financial feasibility is one of the main concerns of management. The success of a project is measured by its financial yardstick, and decisions are made based on monetary forecasts and impact". (Sigurdsson, Thorsteinsson, & Stidsen, 2004).

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[5] International Telecommunications Union (ITU) definition: http://www.itu.int/ITU-T/studygroups/com13/ngn2004/working_definition.html

For the purposes of this research, and as a summary concept, a NGN will be a single network which delivers multiple data applications – whether originally based on voice, data or video – to multiple devices – whether fixed or mobile. In addition, it will be considered that the provision of services is decoupled from networks. Therefore, services have to be supported by infrastructures and have their own network infrastructure-independent evolution.

The NGN architecture (see Figure 2.1) is typically divided into functional planes providing flexibility and scalability to the network (Lee, Lee, Park, Lee, & Bang, 2003; Modarressi & Mohan, 2000). The functional planes are typically separated by open interfaces facilitating interconnection and integration of new services (Kocan, Montgomery, Siegel, Thornberry Jr., & Zenner, 2002), effectively separating the service functions from the transport ones. Thus, apart from the "service domain" that provides coherent end-to-end functionality to the customer and the "control plane" that provides a distributed middleware infrastructure to support services and transport.

The different layers shown are:

- Access network: This is the layer closer to user's premises, used to connect them with the service provider. Comprise a set of different broadband access solutions both for residence and business, using fibre, cable, copper, or wireless/mobile technologies in different configurations. The choice of access technology encompasses among other criteria the costs issue (which in turn depend basically on demographic and geographic variables), possible re-use of existing infrastructures and the user's requirements (and expectations). This plane defines the Next Generation Access Network (NGAN).
- Backbone or Transport network: Collects and distributes communications from / to the Access networks, typically to transport it to longer distances. It also provides the connectivity requested by the service domain with the required QoS, within specified policy constraints, and interconnecting the nodes where data traffic from the access part is gathered to be switched and further transported. The backhaul from distant nodes to the core network is typically included as part of the backbone, although it is convenient at times to consider it separately.
- Core network: Interconnects the Backbone network. Depending on the author is considered separately or belonging to the Transport network.

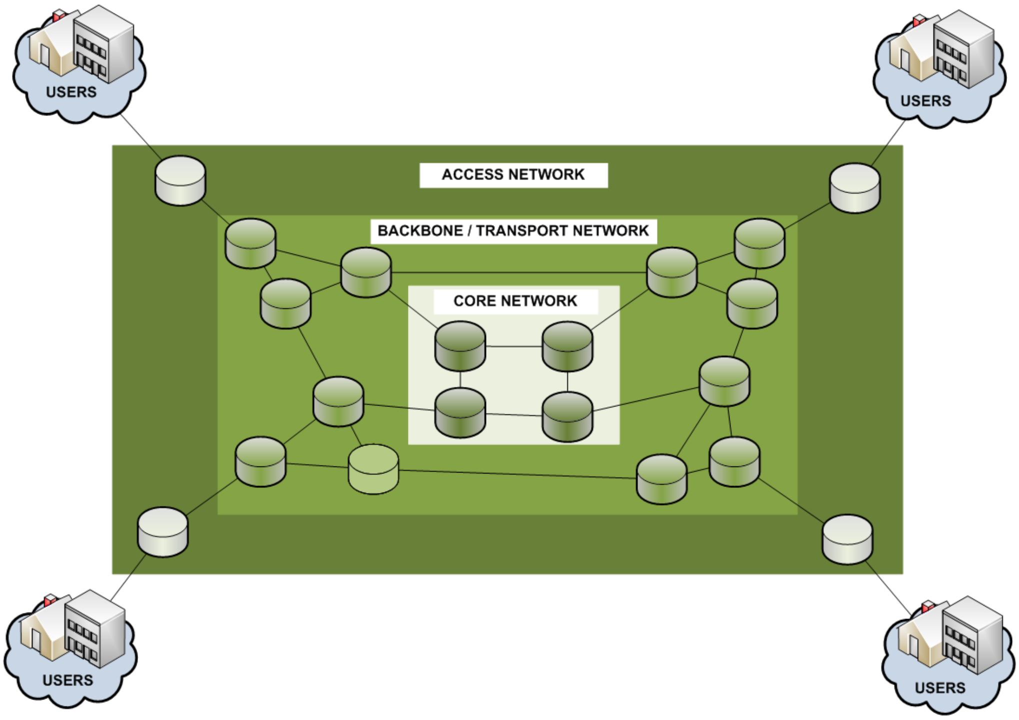

Figure 2.1 –Telecommunication network functional planes

2.2. NEXT GENERATION ACCESS NETWORKS (NGANS)

As already stated the layer that connects subscribers to their immediate service provider is called the access network. The NGAN, consists wholly or in part of optical elements including a significant upgrade to the actually existent network, and is capable of delivering broadband access services with enhanced characteristics (such as higher throughput) as compared to those provided over already existing copper networks (EC, 2010b).

Some sources provide a narrower definition in relation to these network section, as a "wired access networks which consist wholly or partly in optical elements and are capable of providing broadband access to enhanced features compared to services provided over existing copper networks” (CISCO, 2011a). According to this type of definitions wireless networks are not part of NGAN.

Regarding to access speeds provided by a NGAN, it must be pointed out that there is nothing like a strict definition of the minimum threshold in this or in any other quality parameter. A tacit agreement at the industry level seems to put this figure at 50 Mbps, but to prove the vagueness of the case there are no indications whether this number refers to both the upstream and downstream parts or it should be applied just to the downstream channel. Even less is mentioned about the number referring to guaranteed speeds per customer or to just some peak data rate, potentially reachable at times and/or shared among a group of customers.

In any case, there are a number of regulatory decisions and digital strategy plans that implicitly address figures from 30 to 100 Mbps to this regard. Nevertheless the targets and scope of these planes establish regarding the level of access to broadband services to fulfil customers' needs in the short to medium term differ from one to another. The Digital Agenda established: "The 2020 target is internet speeds of 30 Mbps or above for all European citizens, with half European households subscribing to connections of 100 Mbps or higher" (EC, 2010a). The Spanish NRA[6] established in CMT (2008) different conditions for wholesale broadband access below and above the 30 Mbps frontier. The national UK communications, Ofcom, stated "Super-fast broadband is generally taken to mean broadband products that provide a maximum download speed that is greater than 24 Mbps" (Ofcom, 2010). In the US, FCC (2010) establishes as a main objective that "at least 100 million U.S. homes should have affordable access to actual download speeds of at least 100 Mbps".

2.3. CHOICE OF TECHNOLOGIES

In general, broadband access technologies are classified by the physical medium in two major groups: wired – or fixed line – technologies and wireless technologies. The main wired technologies are based on fibre, coaxial, copper wire and power line (this last choice is commonly left aside due to its low implantation and weak mass market prospects[7]). When classifying wireless technologies two main sets of characteristics are considered: being terrestrial or satellite-based and being fixed wireless or mobile wireless. Due to the requisites of NGAN – very high bandwidth for each user- only the terrestrial solutions will be considered in the following[8].

Each of the technologies considered for the study has its advantages and disadvantages in terms of maximum bandwidth/transmission speed, reliability, cost of deployment and ease of coverage. Table 2.1 and Table 2.2 overview some of the main milestones and features of the fixed and mobile technologies involved in the deployment of NGAN compiled from publicly available industry data and forecasts. Given this and other considerations, a particular access solution will be selected by carriers to optimize their existing access systems, if any, and to best match their proposed network services (Dowden, Gitlin, & Martin, 1998). There is not an obvious choice for all situations regarding a specific demographic scenario, and in practice a telecommunications operator will likely use a "mix" of technologies. Considering this implicit assumption that the likely future development of NGAN will come as a combination – including substitution and/or complementarity effects – of technologies, thoroughly analysing their particularities will draw interesting conclusions.

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[6] Comisión del Mercado de las Telecomunicaciones (CMT). http://www.cmt.es/

[7] As an access technology competing with fibre, digital subscriber loop or cable. However it is widely used in the home environment and as part of the smart power grids concept, for further details see for example Pavlidou, Vinck, Yazdani, and Honaty (2003)

[8] For the sake of comparison, according to Eutelsat the next generation of satellites at Ka-band (scheduled to be launched in 2011) will provide 35 times more throughput than traditional Ku-band satellites, will use spot beam technology, and it will be able to provide typically dedicated coverage in 80 set areas delivering shared downstream speeds of 10 Mbps and 2 Mbps upstream to users in those areas.

Table 2.1 – Summary of main milestones in the evolution of fixed NGAN

	FTTH – PtP	**FTTH – GPON**	**FTTB – FTTC - VDSL**	**DOCSIS 3.0**
Data transfer limit (down /up)	40-10 Gb/s 10-5 Gb/s	2,5 Gb/s 1,25 Gb/s	100 Mbps 50 Mbps	400 Mbps 108 Mbps
Usual data rate per user (down/up)	1 Gb/s 100 Mbps	100 – 250 Mbps 50 – 100 Mbps	30 – 50 Mbps 5-15 Mbps	50 Mbps 10 Mbps
EU estimated deployment start	-	2010 – 2014	2008 – 2011	2009 – 2011
Evolved version max. transfer rate	100 Gb/s	10G GPON 10 Gb/s	Advanced DSL 100 – 300 Mbps	DOCSIS 4.0 10 Gb/s
Main advantages	Guaranteed data rates	Guaranteed data rate	Reuse of existing telephone infrastructures	Reuse of cable networks
Significant barriers	Deployment costs	Deployment cost	Opto-electronic equipment	Sharing channels between users

Table 2.2 – Summary of main milestones in the evolution of mobile NGAN

	HDPA (3,5 G)	**LTE (4G)**	**WiMAX mobile (4G)**	**4,5 G**	**Wireless LAN / PAN**
Data transfer limit (down /up)	28 Mbps 5.6 Mbps	300 Mbps 75 Mbps	100 Mbps 50 Mbps	1 Gb/s	10 Gb/s
Usual data rate per user (down/up)	3.6 Mbps 2 Mbps	10 Mbps 2 Mbps	10 Mbps 2 Mbps	100 Mbps	1 Gb/s
EU estimated deployment start	2008 – 2010	2012 – 2014	2012 -2014[9]	2017 – 2020	2014 – 2017
Evolved version max. transfer rate	HDPA+ 84 Mbps	LTE Evolution 1 Gb/s	-	5G	-
Main advantages	Evolution from 3.5 G networks	Evolution from 3.5 G networks	No dependence on existing infrastructures	Evolution from 4G networks	"Smart home" wireless
Significant barriers	Transition technology	Device availability	Business plan development	Technology not mature yet	Technology not mature yet

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[9] May become a niche technology

There are several reasons to include fixed technologies as suitable NGN alternatives. They provide higher access speeds (especially compared to wireless ones), even the improvement of mobile access data rates combined with their ubiquity nature are tightening the gap to decide which is the more convenient deployment in each special case even including the reuse of the existing copper network during the migration. They are also independent of scarce resources as spectrum and more reliable in terms of coverage when used in high density zones. Finally there is the possibility of allocating dedicated broadband resources to the subscribers.

Anyway these fixed technologies have also some disadvantages as the high expense requirements in the deployment stage due to civil works involved, and the fact that in isolated or difficult to reach (due to orography) zones these deployments require higher investments per subscriber.

The subset of NGN which specifically will support the evolution from today's mobile communications infrastructures is usually called Next Generation Mobile Networks (NGMN). NGMN are regarded as a future platform for ubiquitous broadband, facilitating the smooth migration from existing mobile infrastructures, while allowing for the commercial launch of new mobile services and applications. Thus, in the mobile carriers' vision, NGMN will ensure a virtuous cycle of investment, innovation and adoption of services (NGMN Alliance, 2006)[10]. To put it simply, under this perspective NGMN can be viewed as the next step in the evolution of current industry consolidating the heterogeneity of wireless infrastructures managed by mobile network operators (Ramos, Feijóo, González, Rojo, & Gómez-Barroso, 2004). Nevertheless they confront basically the same issues than NGN, but they present in addition some particularities of interest: the need for more –and adequately managed- spectrum, the evolutionary nature of mobile technologies, and their distinctive regulatory model to date (Ramos et al., 2004).

Several reasons vouch for the inclusion of mobile technologies among the alternatives for NGN deployments. As a general consideration, wireless technologies are around 3 to 5 years behind fixed ones in terms of data rates per user. However, they are about to reach the 10 Mbps level per user with some consistency, and some new technologies are approaching the 100 Mbps threshold, at least with regard to peak data rates. This technology choice is also arguably the only economically viable solution for rural and remote areas with very low population density, and the advantages of ubiquitous broadband access for customers are considerable and they could well compensate for lower guaranteed speeds. Additionally a number of experts from the industry forecasted that mobile broadband connections would overcome fixed ones sometime around 2011-2013 (Aguado, 2009; Nerandzic, 2008; Ouvrier, 2008).

As an obvious result from these ambitious roadmaps, mobile networks will require, as already stated, access to new spectrum and/or a much more efficient management of it. Without these spectrum improvements it will be impossible to deploy rapidly enough the required technologies that satisfy users' demands or to compete –and complement- satisfactorily with fixed broadband technologies. In the long run, the massive deployment of femtocells, mobile devices with cognitive radio capabilities and

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[10] NGMN Alliance is an initiative by leading mobile carriers to provide a set of recommendations for the creation of networks suitable for the competitive delivery of mobile broadband services and cost-efficient eventual replacement of existing networks. See http://www.ngmn.org/

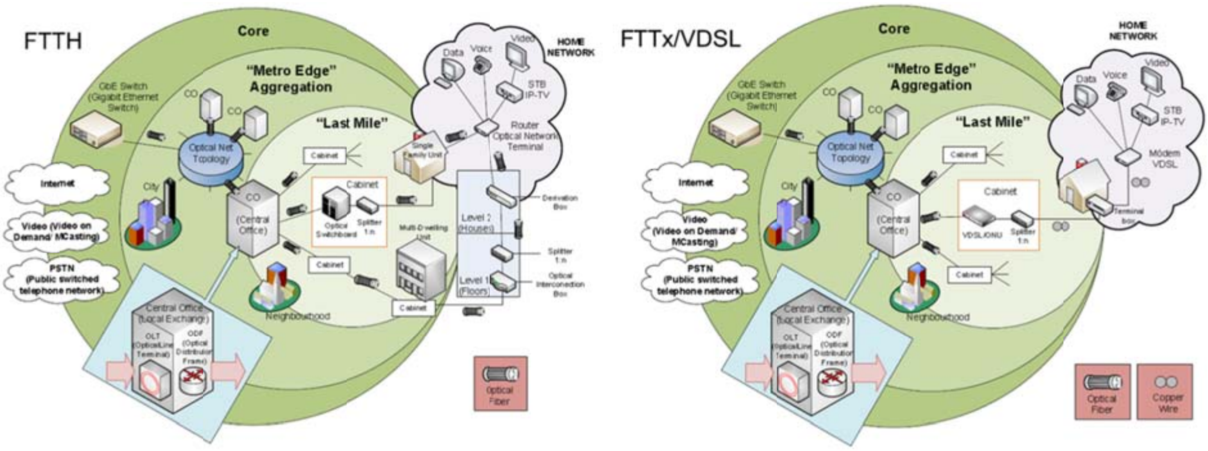
mesh network topologies could make wireless networks almost indistinguishable from most of today’s ultra-broadband fixed solutions. By that time mobile broadband connections will be considered as a suitable (stand-alone or complementary) technological alternative to access technologies.

The technologies chosen for this research are Fibre to the home (in the Point to Point – PtP – and Gigabit Passive Optical Network – GPON – flavours) and Very high Digital Subscriber Line (VDSL) as fixed NGNs, and Long Term Evolution (LTE) as the mobile choice.

2.4. NGN ARCHITECTURES

From the technical perspective, the first assumption considered is that the core backbone and the backhaul network are identical, irrespectively of the technology – or the combination of technologies – chosen for the access part. This access part ranges from a central office (depending on the technology also called local exchange, access node, point of presence-PoP, headend or base station) down to the subscriber equipment (also named “customer premises equipment”, CPE).

Fixed networks topology (Figure 2.2) varies depending on the proximity of the fibre section – that departs from the central office – to the premises.



(a) (b)

Figure 2.2 – Fixed NGN architectures: (a) FTTH; (b) FTTx/VDSL

The taxonomy of FTTx architectures is confusing enough to require some clarification. FTTx is a generic term for technologies that bring fibre from the central office closer to the subscriber. The different types of FTTx (see Figure 2.3) depend on the length of the cooper wire that connects the fibre part to the customer premises. FTTH is therefore a particular case of the architecture in which the fibre follows up from the central office all the way down to the customer’s premise.

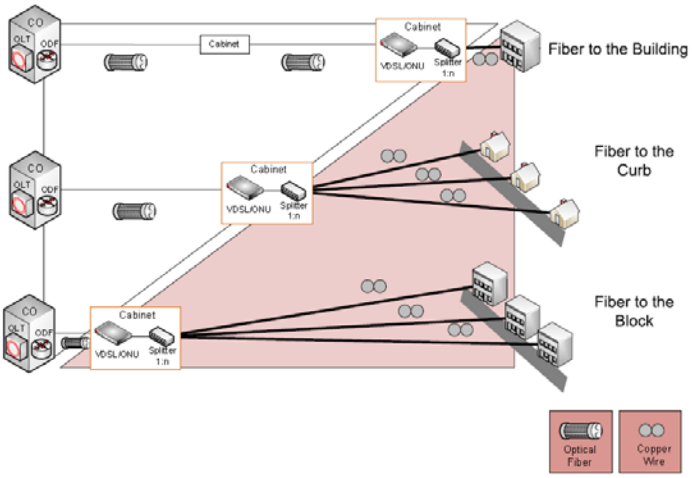


Figure 2.3 – A comparative view of FTTB, FTTC and FTTN

Moving out from the customer premises, in FTTB (Fibre-to-the-building but also Fibre-to-the-basement) the fibre reaches the boundary of the building, such as the basement in a multi-dwelling unit, with the final connection to the individual residence being made via alternative means such as copper wire or a wireless connection. In FTTB the final part of the NGAN not covered by the fibre ranges typically from 50 to 300 meters. FTTP (Fibre-to-the-premises) is a generic term that includes both FTTH and FTTB.

Next choice is FTTC (Fibre-to-the-curb or also Fibre-to-the-cabinet) where the fibre stops at some street cabinet serving a few households (curb) or buildings (cabinet). Again from this point to the customer premises an alternative means is used, typically copper wire 300 to 700 meters long. Finally there is the FTTN architecture (Fibre-to-the-node) where fibre is terminated in a street cabinet about one kilometre away from the customer premises. Note that the copper wire at this distance it is not able to provide more than 30 Mbps with the existing DSL technologies. Therefore, for this reason this architecture has not been usually counted among the NGAN technologies, although this situation can change due to the evolution of technology.

Regarding mobile network architecture (see Figure 2.4), the base station is where the spectrum allocated to the mobile operator is used to connect the subscribers to the network. The data transmission speeds in mobile/wireless system usually refer to the maximum data rate for the whole cell or a sector of coverage of it, always under ideal circumstances. Therefore, real speeds for final customers depend on the number of concurrent users sharing this resource, their proximity to the base station and a number of other events related with existing obstacles and interferences.

To increase coverage in high population density areas or in presence of obstacles – a case most frequent in urban environments – cells are complemented by smaller cells – picocells – serving a reduced number of subscribers. Note that base stations are one of the critical elements in the deployment of 4G technologies, since these require a much higher density of radio stations than 3G to deliver the promised data rates to users.

The other critical element in new wireless systems is the backhaul. The backhauling part of cellular systems can be either by fibre –typical again in urban environments- or by some radio link at specific frequency bands – a usual scenario for remote / rural areas and/or low amount of traffic coming from the cell. There are two main reasons for the relevance of backhauling costs in these networks: its capacity needs to be increased as consumers expand their mobile usage and their data rates in cellular systems sparking a tremendous amount of data traffic across the network, and it needs to be extended to reach the denser network of new base stations. Therefore, it comes as a no surprise the recent interest of mobile operators in the topic[11].

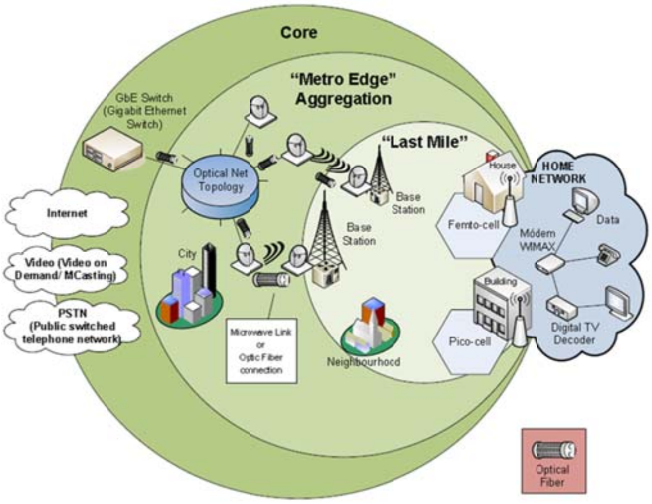


Figure 2.4 – Mobile NGN architectures

2.5. ACCESS NETWORK ARCHITECTURE MODELS

The network architectures presented in this section derive from deployment models used in (Coomonte, Lastres, Feijóo, & Martín, 2012; Feijóo, Gómez-Barroso, & Ramos, 2011) to assess the implied costs in the rollout process of NGA networks. The architectures presented here are used for both energy and cost calculations, thus allowing for a direct comparison of the energy consumption costs with regard to investments, operating expenses, and deployment strategies.

2.5.1. FIBRE TO THE HOME (FTTH)

FTTH technology uses optical fibre to connect subscribers at their premises with two-way transmission speeds of up to 100 Mbps (Kramer, De Andrade, Roy, & Chowdhury, 2012). Continuing improvements in fibre-optic equipment are focused on increasing these speeds without replacing the deployed fibre, creating a "future proof" NGN technology (Europe, 2012).

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[11] Mobile operators have begun to invest in more backhaul capacity. For instance, mobile WiMAX provider Clearwire has said that it will increase its backhaul capacity by 250 percent or more from 2010. Likewise, T-Mobile USA has said it will upgrade to fibre backhaul in more than 100 metro areas in 2010. Verizon Wireless is increasing its backhaul capacity using resources from its wireline wholesale division. And AT&T Mobility has said that it plans to deploy enhanced fibre-optic backhaul connectivity to boost its 3G service as well as prepare for its future LTE service also from 2010.

The different optical network architectures for FTTH basically differ on whether a single fibre is used for a subscriber (point-to-point configurations) or some portion of the fibre is shared among customers (point-to-multipoint). The most common –and cheap- architecture is called passive optical network (PON) and it uses a point-to-multipoint, fibre to the premises network architecture in which unpowered optical splitters are used to enable a single optical fibre to serve multiple premises, typically in the range of 32 to 256. A PON configuration reduces the amount of fibre (and even more important: ducts), power supply and central office equipment required compared with point to point architectures, see, for instance, (Bock et al., 2008) for further details on PON architectures.

Point-to-point Ethernet-based enhanced optical access systems are described in ITU (2010a). These dedicated configurations offer greater service flexibility and are more suitable for infrastructures-based competition. However, those benefits come at the expense of a considerable premium in deployment costs. On the other hand GPON technology is described in (ITU, 2008a). It represents the reference technology for point to multi-point deployments, providing a maximum rate of 2.5Gbps of bandwidth downstream and 1.25Gbps upstream, shared at most by 64 users (ITU, 2008a).

The FTTH market went from 11 million connected homes at the end of 2006 to approximately 86 million at the end of 2011, this is 5% of all households worldwide and 14% of the total fixed broadband market (IDATE, 2012), of which 22% were GPON connections and almost 15% are PtP. Asia dominates this market with roughly 70% of the total market share, with the remaining 30% split equally between the Americas and the EMEA region (Reading, 2011). Currently, the transition from copper to fibre access networks is well underway and will result in the replacement of most copper access networks over the next two decades.

The basic architecture models used in this research for PtP and GPON technologies are shown in Figure 2.5 and Figure 2.6 The connection with the transport layer is accomplished in both cases through a local exchange office in which the energy consumption takes place at the Optical Line Termination (OLT) device. The other primary energy consumption within the network occurs at the customer interface via Customer Premises Equipment (CPE), which utilizes an Optical Network Termination (ONT).

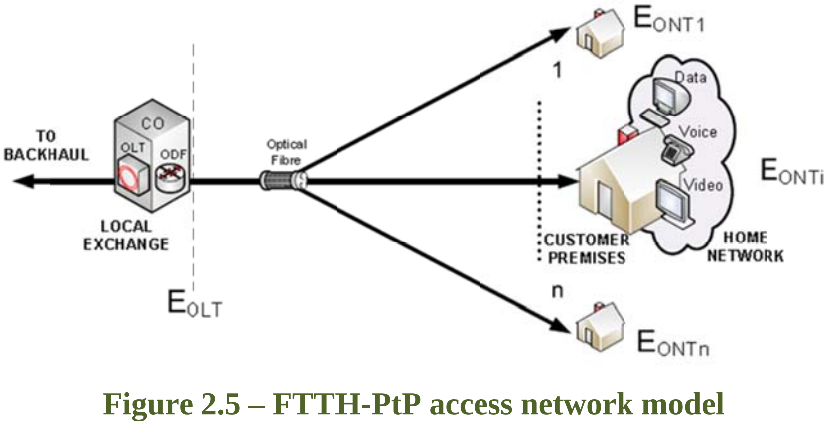

Figure 2.5 – FTTH-PtP access network model

In the PtP case, only an aggregation switch is placed between the local exchange and the customer premises, meaning that less power is required to send the signal through the fibre (Keymile, 2008). In this configuration, it is only necessary to operate the laser diodes that deliver information to the users subscribed to the network service. Customers without service do not need to be connected to an optical port, so the number of premises connected equals the number of premises subscribed. The number of local exchange offices (and therefore of OLT) will depend directly on the number of connected users, the network penetration and the percentage of subscribed users.

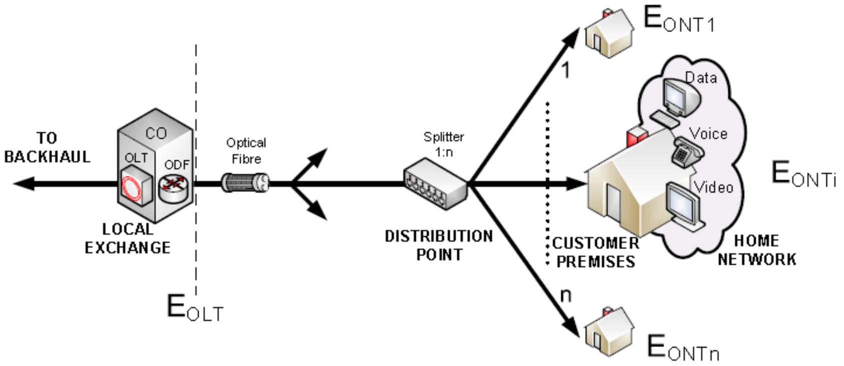

Figure 2.6 – FTTH-GPON access network model

In the GPON architecture, one or more distribution points are placed in between these two extremes, splitting the signal and dispensing it among subscribers. These splitters, as passive devices, do not contribute to the energy consumption of the network, but their number does affect the signal power level transmitted to and from the customer premises. Therefore, the energy consumed at the active devices (OLT and CPE) is typically higher than in PtP networks (Keymile, 2011).

Another difference between these PtP and GPON access network solutions (also observed in FTTx/VDSL deployments) is that in the latter the homes passed are considered to be subscribed homes, and the slot in the OLT is designed to the premise even if no service is provided (Keymile, 2008, 2011). Therefore, depending on the number of subscribed users[12], the service requires a number of interfaces related to the bandwidth allocated to each network subscriber. This requirement translates into network resizing if an increase in bandwidth per user is necessary.

2.5.2.FTTx/VDSL

There is a wide range of different types of technical digital solutions to manage the subscriber loop in the legacy telephone network made of copper wire, known generically as Digital Subscriber Line (xDSL). They differ in the relationship between downstream and upstream velocities (the symmetry / asymmetry), the type of modulations used, the maximum data rates available, and the longitude of the copper

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[12] Note that the number of users (n) served by a single fibre depends basically on the density zone, the level of quality (bandwidth per user) and the requisites derived from possible re-use of existing infrastructures.

wire used. This is precisely the drawback of DSL technologies. Their quality of service decreases with the distance from users' location to the local exchange.

Therefore, to increase the maximum available speed over copper wire, operators can deploy fibre to come closer to users' premises and, from there, connect to (and re-utilize) the final hundreds of meters of copper wire. Then, from the perspective of the architecture of the technology, xDSL solutions are equivalent to FTTx solutions discussed above; their only difference being the perspective adopted: from the copper wire or from the fibre optics side.

FTTx/VDSL technology is defined in ITU (2012). The worldwide number of FTTx subscribers at 2011 represents the 11% of wireline broadband, share predicted to go up to 29% by 2016. In this year almost in the Asian/Pacific region 50% of the wireline broadband customers will be FTTx, while in Europe this rate will be of 16% and 14% in North America (Kunstler, 2011).

In this architecture (see Figure 2.7), the fibre delivered from the central office is terminates at a node/hub/cabinet where an optical network unit (ONU) is placed. This is used to convert signals from the optical network (fibre) into electronic (copper wire, wireless connection or even coaxial cable). This device requires energy to operate, so from the energy perspective it adds consumption to the energy balance. Nevertheless the CPEs allocated have different power requirements than those for FTTH choices as they receive electronic signals instead of optical ones.

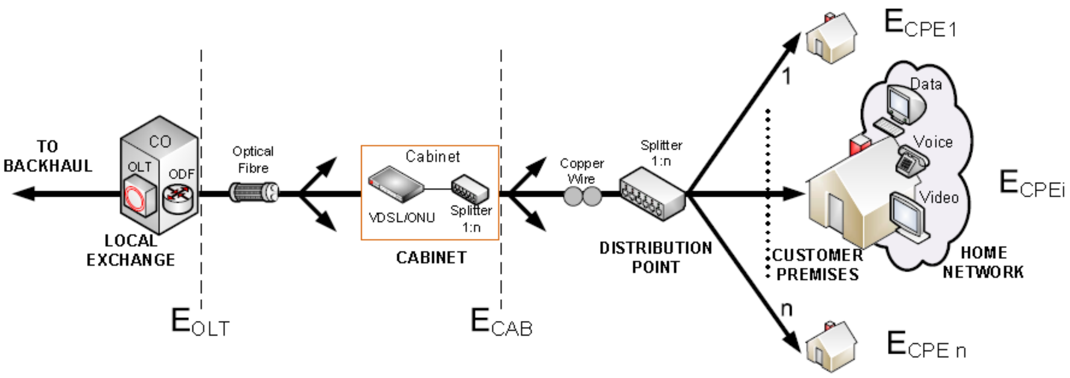

Figure 2.7 – FTTx-VDSL access network model

2.5.3. LTE

LTE was labelled as 4G by the International Telecommunications Union in 2010 (ITU, 2010b), which considered it the natural evolution of the primary 3G mobile communications standards. Rather than a specific technology, LTE is an evolving standard aimed at fulfilling–and eventually surpassing–the International Mobile Telecommunications-Advanced (IMT-Advanced) technical and operational requirements for 4G technologies, specified in ITU-R (2008).

In fact, the figures of LTE deployment worldwide prove the key role of this technology in the evolution of mobile telecommunication networks. After the pioneer system was launched in 2009 by TeliaSonera in Stockholm, the deployment of LTE networks has grown at a high pace. As of March 2013, there were 156 commercial LTE networks deployed in 67 countries—figures that are forecast to increase to 244 networks in 87 countries by the end of 2013 (GSA, 2013). The total number of subscribers reached 70 million at the end of the fourth quarter of 2012. More than half of these are Verizon network subscribers in the US. In addition, more than 660 LTE-enabled user devices were available (more than two and a half times the figure in January 2012), confirming the fact that manufacturers are gradually embracing the migration from 3G to 4G.

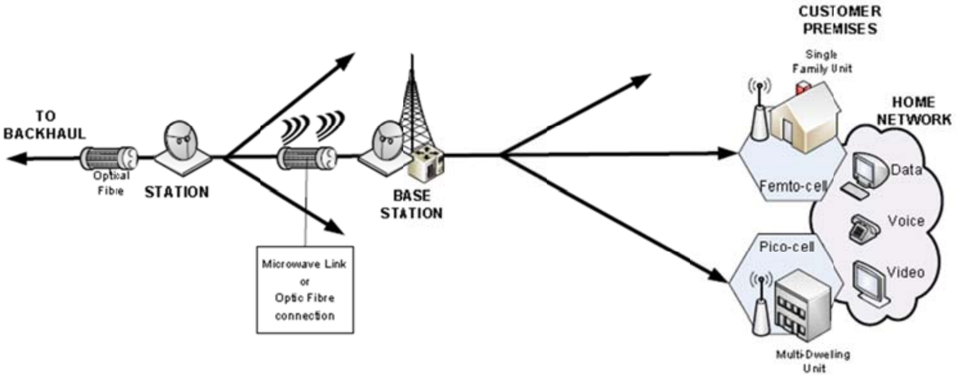

Figure 2.8 – LTE (4G) access network model

In the case of 4G networks the active devices that consume energy in the access section of 4G networks consist of the base stations, the equipment to fill coverage gaps and/or enhance signal quality, and the equipment to interface with users' devices. The base stations are the building blocks of any terrestrial wireless deployment, and the footprint of the network is composed of the coverage area of each base station. From an engineering perspective, the network deployment involves selecting the most appropriate locations for the base stations, given the objectives of coverage and communications quality (Andrews, Claussen, Dohler, Rangan, & Reed, 2012; Schindler, Sadhir, Robbins, Guo, & Paradis, 2011). Additional equipment is needed to fill coverage gaps and/or enhance quality because of physical obstacles to the radio waves emanating from the base stations, especially for indoor coverage. These physical obstacles are typically found in urban areas. Different types of equipment are required depending on the size of the coverage gap: picocells have a coverage radius of hundreds of metres and femtocells of tens of metres (Andrews et al., 2012; Ghosh et al., 2012). In this work, there's no distinction between the two types of equipment; the quantity of equipment required in the network deployment is simply considered to be a function of the number of buildings in the area (not the size of the buildings). In this work, the base stations and picocells/femtocells also correspond to the equipment connecting all types of user devices: handsets, tablets, personal computers, and connected television sets. The unique architecture of mobile networks results in the use of femtocells for CPE equipment (if and when needed) and is therefore not included in the calculations.

Due to the cellular structure of the network, not all the spectrum can be used at a single base station and it shall be divided into neighbouring cells to avoid interferences. The data transmission speeds in mobile/wireless system usually refer to the maximum data rate for the whole cell or a sector of coverage of it, always under ideal circumstances. Therefore, real speeds for final customers depend on the number of concurrent users sharing this resource, their proximity to the base station and a number of other events related with existing obstacles and interferences.

3. DEPLOYMENT SCENARIO

3.1. A GEO-SOCIOECONOMIC SKETCH OF SPAIN

To better understand the past and future evolution of broadband developments in Spain, it is important to first acknowledge some of its distinct geographical, social, and economic features.

From the geographical perspective, Spain is one of the most mountainous countries in Europe, only behind Switzerland and Austria. This fact has caused many difficulties for the extension of every type of infrastructure and, obviously, the broadband telecommunications case has not been different. As a main instance, the universal service for voice telephony was only completed in the 1980s with the use of the so-called TRAC system ("Telefonía Rural de Acceso Celular", cellular access rural telephony), in reality 1G analogue mobile telephony. When Internet access was included as a universal service in the early 2000s, this system for rural areas had to be upgraded. The technologies used in the updated version of the system were mostly General Packet Radio Service (GPRS, 2,5G mobile communications) and also some Local Multipoint Distribution Service (LMDS), allowing data rates equivalent to dial-up modems in those areas. As another main instance, during 2004 a plan for broadband extension in rural areas ("Plan de Extensión de la Banda Ancha", PEBA) was started using regional funding basically to update local exchanges, where possible, to be prepared to provide DSL services.

Related in part with the geographical factors, the distribution of the population is highly heterogeneous (see Table Annex 0.1,Table Annex 0.2, and Table Annex.0.3 in the first section of Annex I). The 29 municipalities with populations over 200,000 inhabitants represent 29.7% of the total population, but only 1.71% of the total surface (INE(1), 2010). At the same time, municipalities which fall within the definition of rural, i.e. population density lower than 300 inhabitants/km^2 (EUROSTAT, 2010), account for 7,401 municipalities of the total 8112, encompassing 33.6% of the total population and 94.8% of the territory. This simple fact explains rather convincingly why many infrastructures reach easily about 60% of the population in Spain and why it is considerably costlier to reach the remaining 40%. Cable deployment is exactly the case.

Another decisive element is the irregular distribution of wealth across regions in Spain, as shown in Table Annex 0.1. For example, the autonomous region of Madrid, with 13.7% of total Spanish population and 18% of Spain's GDP, takes up just 1.59% of the total surface, while Navarra, a region with a similar surface (2.05% of the total) has 1.35% of the total population and its contribution to the total GDP is a meager 1.7% (INE(2), 2010). Broadband deployment is obviously affected by this heterogeneity as shown in Table Annex 0.2: while the average penetration of broadband in households in Spain is 66.7% in 2010, Madrid, the region with the highest penetration, is more than 10 points above (77.3%) and Extremadura –the poorest region- has just a penetration of 57.9% (INE(3), 2010).

3.2. DYNAMICS OF BROADBAND IN SPAIN

3.2.1. ORIGINS AND CHARACTERISTICS OF THE MARKET

Similarly to other EU countries, the dynamics of the broadband market in Spain have broadly followed the three main stages of the electronic communications regulatory framework set out from the EU[13]: the 1998 liberalization process, the new regulatory package developed in 2002 to further competition, and the 2010 framework once some markets (mobile, broadband) were mature and other (fixed telephony) slightly obsolete, and it was necessary to boost ultra-broadband networks.

The development of Internet in Spain began in the 1980s in the context of scientific and technological research. Early developments were conducted in experimental projects mostly at Technical University of Madrid (UPM) jointly with other universities outside Spain. It was also at that time when the first connections in Spain between major universities and research centres in the country were made, as a first step towards the creation of RedIRIS[14] in 1988, a public research network specially designed to support the increasing needs of the Spanish R&D community. The first full connection to the Internet from Spain took place in mid-1990 as an experimental RedIRIS service.

In 1994 the market showed an increasing commercial interest in Internet and some early competition arose, offering connectivity services. However, the turning point in Internet development took place in 1995[15] following the entry into the Spanish market of Internet transit services of large telephone (Telefónica, BT and Sprint) and

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[13] Given the market power of Telefónica it would've been impossible to introduce competition (unbundling for example) without regulation coming from Brussels. In general at national level the action taken has been rather reactive instead of proactive.

[14] As of 2013, RedIris is the public ISP offering connectivity and advanced services to universities, research centres and other parts of the public administration in Spain. RedIris is the Spanish partner in the European Geant network. RedIris administratively is part of Red.es, the Spanish public agency for the development of the information society, in turn belonging to the Ministry of Industry, Tourism and Commerce.

[15] At that time, Spain was still in a position far behind other countries in Internet development, given the high cost of connectivity fees. Thus a user, in addition to the supplier's invoice, had to pay the cost of the call to the closest node, which for most meant the payment of international charges. This prevented mass adoption and was the main reason why in 1995 Spain only had 30000 Internet users.

computer companies (IBM, ICL-Fujitsu). As a direct consequence, more than 20 new suppliers appeared in the market. Nevertheless broadband access had a merely testimonial presence in the residential market before the first stage of liberalization, which took place during 1999-2000.

From 1999 to around 2004 the broadband market was dominated by ADSL technology –provided by the incumbent Telefonica and a number of ISPs that used basically bitstream access regulation. Cable modem technology was also relevant, but just in those places where cable operators were present in the market[16]. The broadband penetration (subscriptions per 100 inhabitants) was just 5% in 2003. From 2004 to present, service-based competition has significantly increased with the adoption of local loop unbundling regulation (xDSL technologies), while on the contrary facilities-based competition has stagnated due mainly to the financial difficulties of cable operators that have almost completely stopped the deployment of new infrastructures due to the intensive investment they have undertaken along the last decades[17].

The latest data available from CMT (see Table 3.1 for details) establish a broadband penetration of 24.7% (11,624,680 broadband subscriptions), composed of 78.1% of xDSL lines and 19.25% cable modem lines. Next generation access networks (NGAN) based on fibre (FTTx technologies) have a shy deployment reaching only 1.59% market share (see Figure 3.1).

Table 3.1 – Compilation of data on broadband markets in Spain.

Indicator	
Fixed BB subscriptions (January 2012, CMT)	11,624,680
Fixed BB penetration (per 100 inhabitants) (Jun. 2012, OECD)	24.7%
Fixed BB penetration growth year-on-year (% subscribers per 100 inhabitants) (Jun 2012, OECD)	0.95%
Mobile wireless BB subscriptions (June 2012, OECD)	22,277,983
Mobile wireless BB subscriptions (per 100 inhabitants) (June 2012, OECD)	48.3%
Households with broadband access (INE 2012)	66.7%
Coverage of xDSL networks (% population) (April 2009, OECD)	96.1%
Coverage of 3G networks (% population) (End 2008, OECD)	83%
Availability of cable modem services (% households) (2007-2008, OECD)	60.2%
Availability of FTTH/B (% households) (End 2008, OECD)	1.5%

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[16] About 45% of total premises at the end of the period, according to data from Spanish NRA (CMT, 2010b).

[17] According to OECD data from June 2010 (OECD, 2010b), the xDSL penetration in Spain was 18% (number of xDSL subscriptions per 100 inhabitants) while the cable penetration was 4.1%. Also the percentage of cable broadband connections in the total number of broadband subscriptions has slowly dropped from 25.2% in 2003 to 20% in 2009.

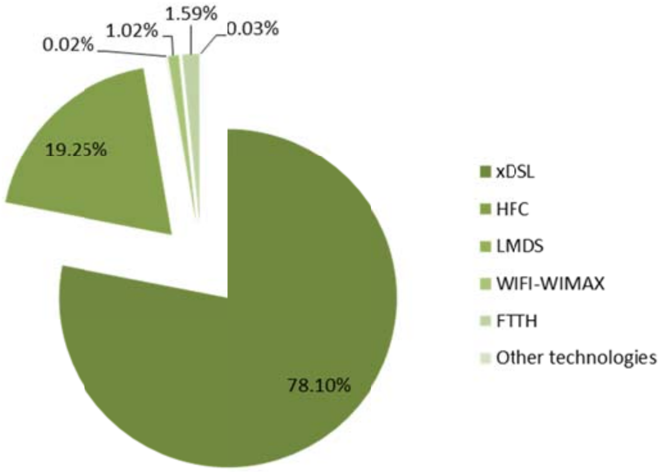

Figure 3.1 – Breakdown of BB lines per technology IVQ 2012

Spanish broadband market has a number of distinct features worth to explore in detail. The first of them is the combination of below-average adoption and above-average level of availability of broadband connectivity (DSL technologies, fundamentally) in comparison with similar countries[18] (see detailed figures in Table 3.2 and Table 3.3). This mismatch of supply and demand is more intriguing when taking into consideration the difficulties in the deployment of broadband infrastructures. In Spain there is a significant amount of rural areas with relatively low density of population and considerable geographic barriers.

Table 3.2 – Spain vs. average EU-27 broadband market (EC, 2010d)

Data	*Spain*	*EU-27*
Fixed BB penetration	23.20%	25.60%
Fixed BB penetration growth 2010	0.97%	0.86%
DSL lines	80%	78%
Cable Modem lines	20%	22%
BB Speed: Above 144 Kbps and below 2 Mbps	9.43%	13.3%
BB Speed: 2 Mbps and above and below 10 Mbps	62.43%	57.5%
BB Speed: 10 Mbps and above	28.14%	29.2%
Mobile BB Penetration	23.10%	21.30%

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[18] According to OECD data from 2009 (OECD, 2010b), Internet access through DSL technologies were available in Spain for 96.1% of population while the OECD average remained at 88%.

Table 3.3 – Spain rankings in the EU-27 context (EC, 2010d)

Data	*Spain level*	*Ranking*	*Reference Country (Level)* [19]
Total DSL coverage (as % of total population)	93%	17	Belgium, Denmark, France, Luxembourg, Sweden, United Kingdom (100%)
DSL coverage in rural areas (as % of total population)	90%	9	Belgium, Denmark, France, Luxembourg (100%)
Broadband penetration (as % of population)	21.5%	16	Denmark (37.8%)
Speed — % of broadband subscriptions above 2 Mbps	89.3%	10	The Czech Republic (100%) - year 2008 data Greece (100%) - year 2009 data
3G+ coverage (as % of total population)	80.2% (2008)	15	Malta (100%) - year 2008 data
% of households with an internet connection	54%	21	Netherlands (90%)
% of households with a broadband connection	51	15	Sweden (79%)
% of enterprises with a (fixed) broadband access	94	2	Finland (94%)
% of population using a mobile phone via UMTS (3G) to access the internet	9	5	Sweden (14%)

The structure of the market, and competition within it, is also peculiar. Telefonica, the national incumbent operator, preserves a market share in broadband higher than the average of European comparable cases[20]. Cable in Spain (composed of ONO as the main operator and some other regional operators) was only deployed from the mid-nineties onwards and remains limited fundamentally to urban areas with relatively high density of population. The resulting competitive panorama in broadband fixed technologies is a blend of infrastructure-based competition and service-based competition (alternative operators using the infrastructures of the incumbent) in urban areas and a mostly sole incumbent presence in suburban and rural areas (with some regional exceptions). As a consequence, facilities-based competition in the form of a duopoly is intense in those areas where cable is present while in the rest of the territory competition only happens through the incumbent infrastructures. In spite of the situation, and however tempting, regulation based on geographical segmentation has never happened in Spain. As an overall market result, broadband prices in Spain are higher than the average in comparable EU countries[21] and the most frequent speeds lower[22] (see Figure 3.2).

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[19] This refers to the rate of the country with the highest value in the EC Ranking.

[20] Only Finland (68.0%), Denmark (62.3%) and Italy (55.5%) have a higher share of incumbent broadband subscriptions than Spain (53.5%) as of July 2010. See: Broadband access in the EU: situation at 1 July 2010, Digital Agenda: broadband speeds increasing but Europe must do more. Available at http://ec.europa.eu/information_society/newsroom/cf/itemlongdetail.cfm?item_id=6502

[21] The study on broadband pricing in Spain CMT (2010a), issued by the Spanish NRA (Comisión del Mercado de las Telecomunicaciones, CMT), indicates that during June 2010 the best offer for broadband at medium speeds (2 Mbps to 10 Mbps) was 21% more expensive than the EU average at prices adjusted for purchasing power parity (32 € PPP in Spain to 26.4 € PPP in the EU on average). At speeds above 10 Mbps the difference was 29% above the EU average while in the low speeds range (below 2 Mbps) the difference was 10% above the EU average.

[22] According to OECD data compiled in Oct 2009 (OECD, 2010a), Spain is the sixth among the 31 countries surveyed with the lowest average broadband download speed.

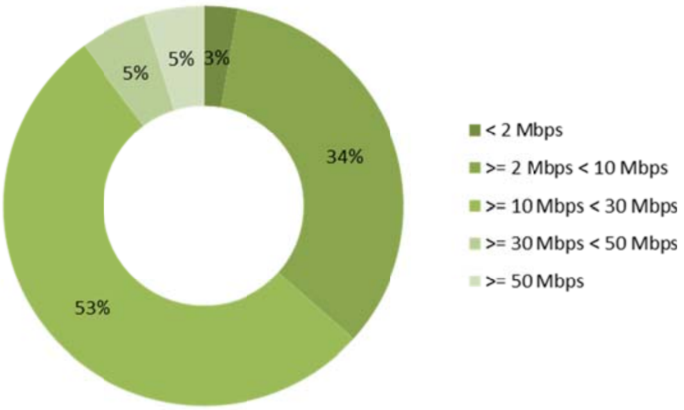

Figure 3.2 – Breakdown of BB lines per speed in IVQ 2012

Also partly because of the structure of the competition in broadband markets, partly due to Spanish lifestyles and partly to the public administration structure, there are two other characteristics worth to mention in Spain with regard to the dynamics of broadband markets in particular when looking into the future: the constant interest in the use of wireless technologies to complete broadband availability (with a very favourable response from the demand side), and the deep involvement of local and regional administrations in all forms of broadband encouragement and even deployment.

3.2.2.FIXED BROADBAND IN SPAIN

On December 1, 1998, the Spanish telecommunications market was opened to the introduction of full competition. At that time, Internet access represented 0,3% of the sector's overall turnover. It consisted of traditional telephone line access and until 1999 there was no commercial high-speed (broadband) data access service offer. Indeed, it was this year when two events marked the start of the commercial broadband offer in Spain. On the one hand, a decree was passed forcing the former monopoly (Telefónica) to provide indirect access to its client's subscriber loops. On the other hand, cable operators, who had won their (regional) licenses in tenders awarded basically in 1998, started their commercial operations.

The market developed quickly and during 2002 the first million broadband accesses were reached. However, it must be noted that until the first months of 2004, there continued to be less broadband accesses than switched Internet accesses (Figure 3.3). Between 2002 and 2006, the growth curve was steep. Growth slowed down from that moment on and in the last years, the market started to show the first signs of maturity.

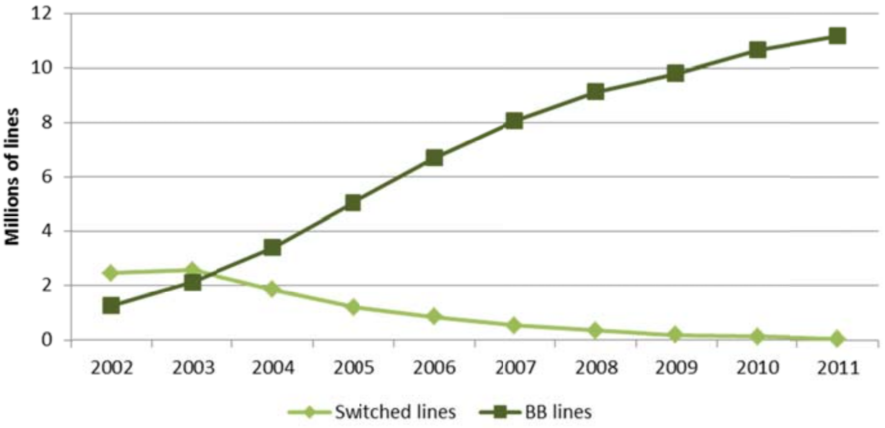

Figure 3.3 – Evolution of switched and broadband access lines (millions of lines).

The 10.65 million broadband lines operating in 2009 (Figure 3.4) represented a penetration of 23.2 lines per 100 inhabitants[23], a value below that of the European Union average at the time (25.6). Considering the number of households instead of inhabitants, the penetration rose to 51% (56% in the EU). The geographical distribution of these accesses is not even and thus, for example, penetration in Madrid and Barcelona provinces' was well above the European average.

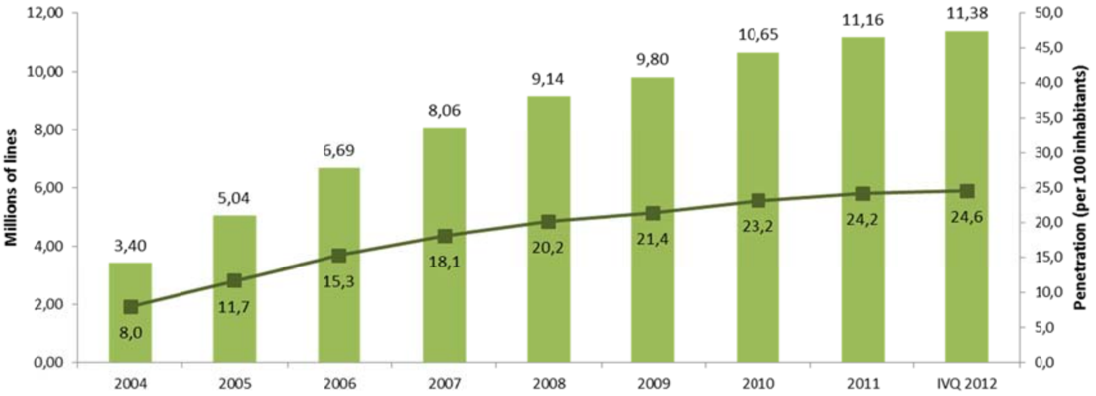

Figure 3.4 – Detailed evolution of broadband access lines (millions of lines and penetration per 100 inhabitants)

Despite the early awarding of licenses for fixed wireless access and the subsequent introduction of other technological options, the indisputably predominant access technologies have been -and are- xDSL and cable networks. Both represented, in 2011, more than 97% of the residential market income and 95% of the business market.

When measured by number of lines, the picture is similar: the remaining technologies' presence is almost symbolic. Cable accesses represented 19.25% of the market at the end of 2012. Although slowly, during the last years cable has lost some

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[23] For 2010, at the time of release of this chapter, only basic data regarding October are available. At that time, the number of lines had reached 10.4 million, representing a penetration of 22.3 lines per 100 inhabitants.

share to xDSL accesses. In any case total BB access penetration has steadily grown over last seven years as can be shown in Figure 3.4 (further details in Table Annex 0.5).

Another trend that has progressively defined itself in time is the bundling of broadband with other services. In 2005, three out of every four clients hiring broadband also hired one or more additional services. By the end of 2007 this percentage exceeded 90% and in 2009, it represented 95.6% (75,1% hired broadband with voice; 1.6% with television and 19.0% with both: voice and television).

Last, it is necessary to note that broadband is not a cheap service in Spain. In order to overcome the difficulty of resolving how multiple and different offers should be considered, data of a survey carried out in 3000 households (in October 2009) (Red.es, 2009) is used for this purpose. According to this survey, the average expense per household for a bundle including broadband and voice was 42.8 €[24] (per month, line fee included). In the case of a triple bundle, that is, including television service, the average expense per household reached 54.2 €/month.

3.2.3. MOBILE BROADBAND IN SPAIN

It is unquestionable that the deployment of new generations of mobile communications technologies, 3G and beyond has changed substantially the scenario of broadband access. In practice mobile technologies have become a platform able to complement – but also increasingly able to compete with – traditional fixed broadband access.

From about the year 2000 Spanish mobile operators were well aware of the opportunities involved in mobile broadband services. In fact the Spanish Government was the second EU Member State - after Finland- in trying to launch the UMTS 3G technology: the process for granting four licenses for the new technology was initiated on 10 November 1999. The Government opted for a beauty contest (with a fee per license of 129.2 million €), which resulted on 10 March 2000 in the three existing operators at the time (Telefonica, Airtel –now Vodafone-, and Amena –now Orange-) receiving a 3G license and a fourth new license for Xfera (now Yoigo).

From the regulatory perspective, the model in place has supported the cycle of investment – renewal of technology. In fact, it can be said (Ramos, 2005) that the competitive scenario of mobile communications in Spain – and in most European countries- is characterised by a “light handed” approach where the basic instrument has been the introduction of new operators using the shifts in technology generations. Therefore the level of competition was increased one step at every time that new licenses where granted and even additional licenses were granted in exchange of the operators’ compromise to complete the coverage in underserved areas. As a result, it comes as a no surprise, the difficulties in refarming spectrum in Spain due to the asymmetries in the licensing process.

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[24] As a reference, the legal minimum wage in Spain in 2010 was 633.30 Euros per month.

Table 3.4 – Mobile communications generations in Spain.

Technology Generation	*1G*	*2G*	*2,5G*	*3G*	*3,5G*	*4G*
Year of commercial launch	1983	1995	2001	2004	2006	2013 (expected)
Standard	TACS	GSM	GSM/GPRS	W-CDMA UTRA FDD / TDD (UMTS)	HSPA	LTE
Maximum downstream data speed available	9.6 Kb/s	9.6 Kb/s	64 - 144 Kb/s	384 Kb/s - 2 Mbps	7.2 - 40 Mbps	100 Mbps (expected)

Thus, the mobile regulatory model in Spain has been directed to promote facilities-based competition and, as a consequence, the vertical integration ("silo model") of infrastructures and services. Within this model, the necessary conditions were set for the operators to bet on a continuous investment in networks and infrastructures, a must for mobile technologies where the life cycle of assets is much shorter than in fixed technologies. The result has been a virtuous circle of investments and innovation where prices for consumers have decreased following a soft glide path that has favoured the recovery of investments and the innovation in next technology generations. The level of investment has been kept at a high level and in particular the transition to 3G networks has increased it further from 2005 onwards.

This level of investment has impacted the coverage of mobile communications both in terms of population and territory. In particular, mobile broadband coverage was already at 85% of the population in 2007 and beyond 90% in early 2010 (CMT, 2009a). Coverage of the territory is among the highest of the "large" countries in Europe (only the UK has it slightly better) and it is above the average of EU-15 (at 83%) and well above the average of EU-27 (at 77%) in spite of the comparatively low density of population and its dispersion in Spain.

3.2.4. DEVELOPMENT OF NGNS IN SPAIN

The mentioned uncertainties on the deployment of NGN, together with their role as basic infrastructures of the information society / knowledge economy have prompted a growing amount of studies, reports and papers from the industry, regulation authorities and academia about the circumstances for their future deployment, see for instance the report on the deployment of fibre networks commissioned by Ofcom in the UK (Analysis Mason, 2009).

In the case of Spain, there is an equivalent report from the Spanish NRA (CMT, 2009b), on the prospective of fibre deployment in Spain. The main conclusions, drawn from the report, are:

- Keeping in mind the large investments required, the deployment of FTTH networks will be carried out gradually, both with regard to time frames and with regard to the different geographical areas. Operators will carry out selective investments by area, starting in areas where deployment costs are lower and estimated income is higher. These areas typically tend to be urban areas that are more densely populated, and the operators who arrive first will be at an advantage over the rest, and this will be reflected in their investment recovery periods.

- In 2023 (15 years period since the investments in fibre optics were supposed to begin in 2008) between 43% and 46% of Spanish households will have fibre-to-the-home (FTTH) internet access.
- Madrid and Barcelona are the two most likely cities for such a deployment due to their economic potential and their high population density, which will be able to support the presence of between two and three other fibre optic networks in addition to Telefónica's, within a 15 years period.
- There may not be sufficient demand to incentivize the presence of any alternatives other than Telefónica in less populated areas. In such cases, due to the lack of attraction in terms of investment, actions from public authorities would be desirable. Alternative operators would have practically no presence in smaller municipalities (those with less than 1,000 inhabitants) and, if they were present, they would take more than 15 years to recover their investment. Municipalities with populations between 1,000 and one million inhabitants could have FTTH network access provided by one alternative operator in competition with the incumbent, within the 15 years period time frame. In municipalities with more than 50,000 inhabitants, the alternative operators that deploy fibre optic networks would be able to recover their investment within a time period of 9 to 12 years at most. The investment recovery period for municipalities between 5,000 and 50,000 inhabitants would be between 13 and 15 years.

In the same line, previous research on the investment required to encompass these deployments identifies a baseline for ultra-broadband market behaviour (see Figure 1.1 in Chapter 1). In 2015 it would be relatively possible for Spain to enjoy a "2+" infrastructures-based competition (incumbent, cable operator and mobile operators) for NGAN at about 50% of premises (i.e., 9 million of households and businesses). Beyond this point the required investments would be much higher. No regulatory action seems able to easily increase the investment in the required zones, and neither a huge public effort to compensate lack of pure market action seems possible under the current economic conditions. The role of the mobile operators in the competitive landscape should also be considered under the light of NGAN having a tendency to decrease the number of competitors due to the level of investments required. Their irruption in this market can increase the chances of a healthy competition.

Obviously, these scenarios have prompted some debate and the launch of a number of political and regulatory initiatives, apart from the communications and guidelines from the EU. Thus, the first document of relevance was the CMT "Principles and master lines for the future regulation of NGANs" (CMT, 2008), which served as a guideline, analysing the feasible regulatory options. A number of additional documents (CMT(1), 2009; CMT(2), 2009; Commission, 2009, June, 2009, September, 2010, September) have continued to define the path for the evolution of NGAN in terms of regulations. In addition a number of public initiatives have been used to supplement and substitute private initiative as depicted in Figure 3.5.

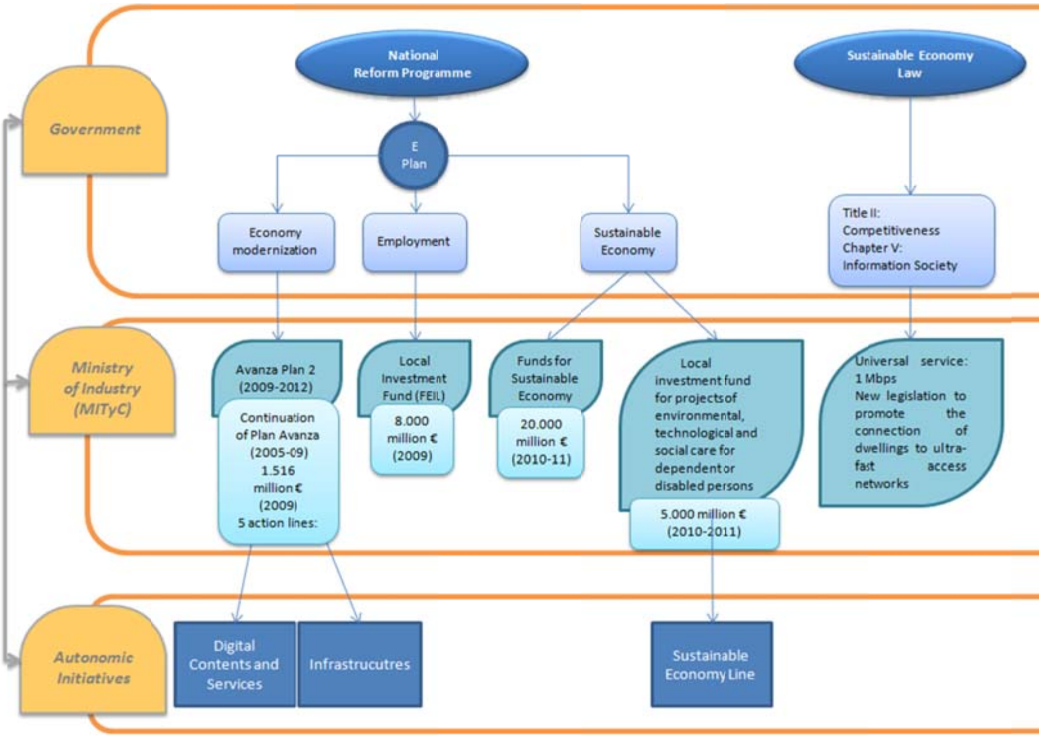

Figure 3.5 – Summary of national public initiatives in relationship with the deployment of broadband and NGN. Source: FEDEA[25]

Within this framework, in general terms it can be said that NGAN deployment is currently in an incipient stage – particularly out of main urban areas – and is very limited regarding the status of deployment (see Table 3.1) and the coverage map (see Table 3.5).

While currently, the broadband network coverage map in Spain is well over the OECD average in xDSL (96.1%), 3G (83%) and cable (60.2%), and the percentage of households and business passed is higher than in countries like Germany or United Kingdom (but with lower subscribers figures), the FTTH coverage (1.5%) is much lower in relation to OECD average (OECD, 2010c). Another data that illustrates the scarce NGN deployment in Spain is its low number of subscribers: 0.3% of the total broadband subscriptions had FTTH lines in 2010 (OECD, 2010c), especially in comparison to other neighbouring countries. For example, Spain had 26726 FTTH users in July 2009 while France had 60000 users in the same period according to EU reports.

The latest data available (FEDEA, 2010), depict the current NGANs situation shown in Figure 3.6 (for details see Table Annex 0.7), combining networks currently in use (red) and in prospect deployments (green).

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[25] See http://www.crisis09.es/redes/aapp.html

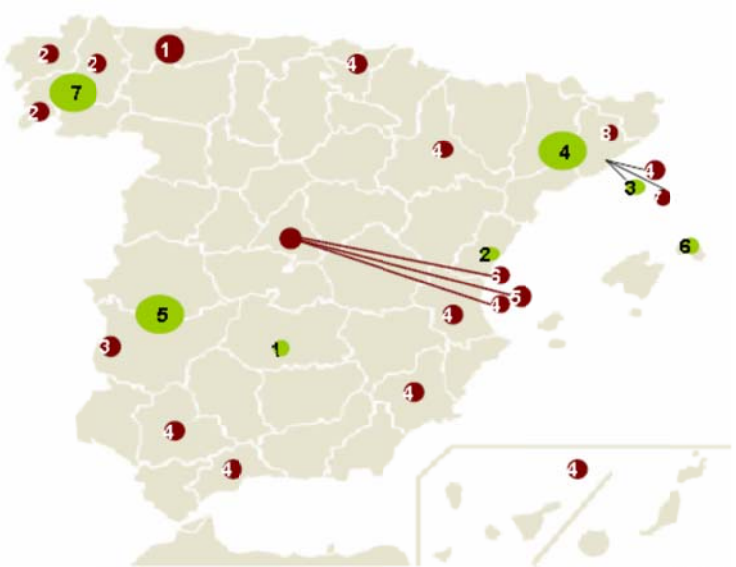

Figure 3.6 – Spanish NGAN map

Table 3.5 – NGN coverage in Spain.

Company/Coverage	*Households*	*Business*	*Users*	*Villages*	*Provinces*
Red Asturcón	51,000		7,322	45	Asturias
R	450,000				A Coruña, Lugo, Ourense, Pontevedra
Cablex	2,750		500		Badajoz
Telefónica			11,306		Sevilla, Málaga, Múrcia, Madrid, Valencia, Barcelona, Zaragoza, Vizcaya, Álava
Ono	14,741	67,000	1,825,000		Madrid
Orange	-				Madrid
Adamo	-				Asturias
					Barcelona
Guifinet	-				Barcelona
Nostracom					Asturias, Badajoz, Ciudad Real, Valencia, Sevilla, Cádiz, Granada y Almería

The interest of main telecom operators in investing in NGAN development is rather modest, with only some commitment from cable operators to deploy DOCSIS 3.0 in their existing plant and FTTH initiatives from regional operators like Telecable.

Regarding to the public initiative, there can be found both regional and local initiatives for broadband development (see Table Annex 0.8) and NGN deployment (see Table 3.6. Regional initiatives are based on public ownership with public, private or even concession models for network management. Local initiatives have been emerging recently almost everywhere in Spain, although most of them are still in the planning stage. They have in common that they belong to municipalities where there is a deep sense that digital divide should disappear, so the investment in NGN seems rather necessary. Obviously, these initiatives are tremendously scattered and depend strongly on political perspectives and currently on many economic constraints.

Table 3.6 – Initiatives for regional public-private NGAN deployments in Spain.

Public Administration	*Project*	*Nature*	*Geographical Area*	*Goal*
Principado de Asturias Government	Asturcón Network	Public Investment	Asturias	Fibre to the the Home Deployment in 53.000 households and villages
Generalitat de Catalunya	Xarxa Oberta	Public & Private cooperation	Cataluña	Fibre deployment for public administration & Wholesale market for 947 municipalities (281)
Galicia	Broadband Plan 2010-2013	Public	Galicia	Ultrabroadband for 200 villages & 1 million population
Consell Insular de Menorca	Fibre to the Home	Public & Private cooperation	Menorca	Wifi Network for citizens & business; trunk Fibre network & FTTH

Table 3.7 – Summary of next generation network deployment cases presented for approval at the EC

Case Number	*Last Decision Date*	*Title*	*Budget assigned*
N304/2010	17.12.2010	Plan Avanza	>5 kmillion €
N323/2009	14.12.2009	Broadband in rural areas of Asturias	6.5 million €
N407/2009	11.08.2010	Optical Fibre Catalonia	354 million €
N424/2010	10.11.2010	Ayudas para el despliegue de infraestructuras de banda ancha en el marco del Plan Director de Banda Ancha de Galicia 2010–2013	67.73 million €
N699/2009	12.08.2010	Desarrollo del programa de infraestructuras de telecomunicaciones en la Región de Murcia. - TO BE DEFINED	25 million €
SA.33099	24.08.2012	High-speed broadband in Rioja	--

3.3. METHODOLOGY FOR THE CLASSIFICATION AND DISTRIBUTION OF THE DEMOGRAPHIC SCENARIO

The baseline presented in this research is placed in the specific demographic framework of Spain (see a summary of the demographic data in Table 3.8 and for further details in the first section of Annex I – Additional Tables). Aside from the direct relevance of the case for Spain as a primary European example for NGN deployment, it is interesting to note that data for Spain is relatively similar to the "Euroland" scenario (Forge, Blackman, & Bohlin, 2005), thus enabling its easy extension for similar countries[26].

Table 3.8 – Summary of the demographic data of the Spanish scenario

Case Number	*Last Decision Date*
Number of municipalities	8,112
Total population (inhabitants)	46,745,807
Average population (inhabitants per municipality)	5,763
Total surface (km^2)	504,677
Average surface per municipality (km^2)	62.21
Number of households and business	17,950,398
Number of buildings	9,285,007
Mobile penetration rate (CMT, January 2012)	125.3%
Total number of mobile users	56,562,426
Global average mobile users per premise	3.15
Global average mobile users per building	10.08

The demographic framework classifies each municipality into 10 different geographical zones[27] (numbered I to X) based on their population density[28]. While other studies (Analysys Mason, 2009; Forge et al., 2005; J. Gómez-Barroso, Robles-Rovalo, A. , 2008; Jeanjean, 2010) typically divide the territory into 3 to 8 zones, this division into 10 zones allows for more accurate estimations in the "grey" areas with intermediate population densities, a key aspect of NGN deployment (J. L. Gómez-Barroso & Feijóo, 2010b). In fact in the case of Spain about one quarter of the population lives in the 500 – 100 inhabitants/Km^2 area, where the population density typical of suburban zones finishes and the rural type-of-density begins. About 46% of the population lives in urban areas (above 1000 inhabitants/Km^2), with an additional 10% in lower-density

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[26] Apart from the direct relevance of the case of Spain as a main European instance for NGAN deployment, it is interesting to note that data for Spain are relatively similar to the Euroland scenario (Forge et al., 2005). The population in this area adds up to 46,4 million inhabitants, which is the mean of seven European states: France, Germany, Italy, Holland, Spain, Sweden and the United Kingdom. Demographically, Euroland is made up by a few urban areas with a high population density, a greater number of suburban areas, many rural areas and very few remote areas. Last, there are 15.4 million households in Euroland and, of the total inhabitants, 17.3 million are employed in 3.2 million companies.

[27] Previous studies usually considered 3 to 7 zones. For instance, in the Euroland scenario (Forge et al., 2005) it was assumed that 50% of the population lived in urban areas (6,000 inhab/km2 population density), 35% in suburban areas (500 inhab/km2 density) and around 15% in rural areas (30 inhab/km2 density). Gómez-Barroso and Robles-Rovalo (2008) chose a division into 7 zones for WiMAX calculations in México. This is also the number used in Jeanjean (2010) for NGAN calculations. Analysis Mason (2009), apart from London, also selected 7 zones for its study on fibre deployment in the UK, however leaving aside the rural and remote areas.

[28] The other basic option would have been to choose the city/town size, which could give an indication of deployment priority but does not capture well enough the situation in rural areas or for wireless deployments, see Analysis Mason (2008, p. 35) for a discussion.

suburban areas. Remote rural areas (below 50 inhabitants/Km^2) made up 12 % of the population.

Table 3.9 – Density zones distribution features

Zone	I	II	III	IV	V	VI	VII	VIII	IX	X
Range of density (inh/km2)	> 10 000	10-5 000	5-3 000	3-1 000	1000 – 500	500 – 100	100 – 50	50 – 10	10 – 5	<5

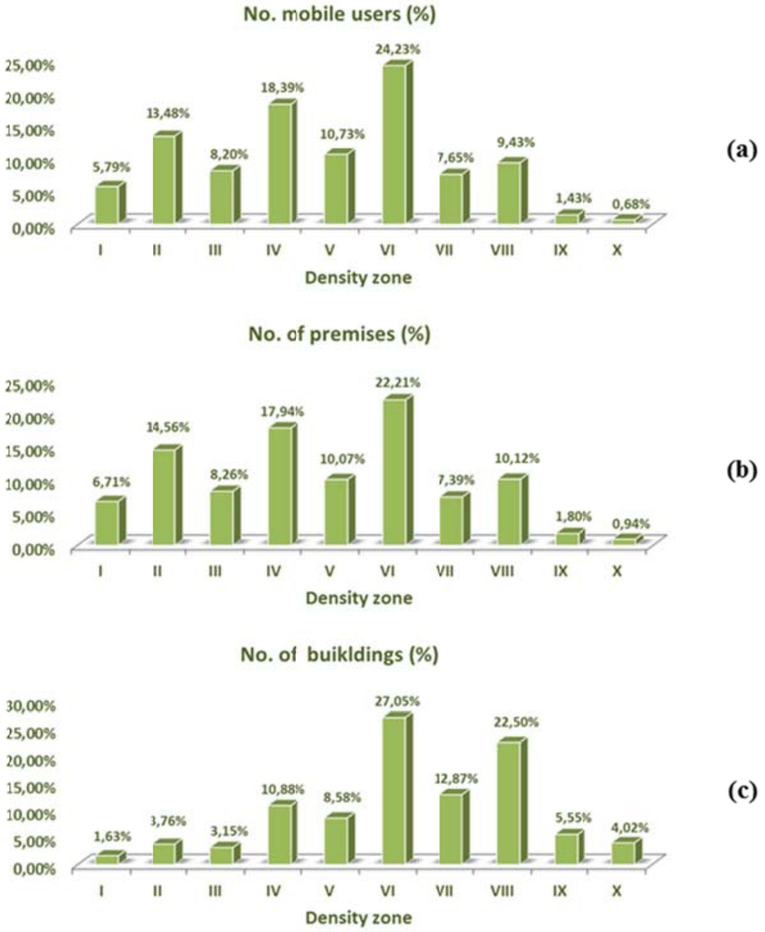

Figure 3.7 – Distribution of mobile users (inhabitants) (a), premises (b), and buildings (c), in the different density zones of the Spanish scenario

The main drawback of a classification based on population density is the lack of information of buildings clustering mainly in suburban and rural areas. Information on which part of a municipality is densely built and which has only scattered buildings allows for a more precise characterization of suburban and rural areas. This is a key element for the proper dimensioning of networks, as base stations and local exchanges need to be located in a denser pattern in those places where buildings are also more densely placed

Therefore, to enhance the modelling of the deployment costs, each of the zones has been divided into two types, (a) and (b), resulting in a total of 18 geotypes for the calculations (in zones IX and X the population density is so low that all population is assumed to be distributed according to the b model). The key element for this additional categorisation is the location of the local exchange or base station. For instance, exchanges tend to cover the central core of a settlement and, at the same time, some wider areas where the settlement is sparser (Analysis Mason, 2008), as shown in Figure 3.8.

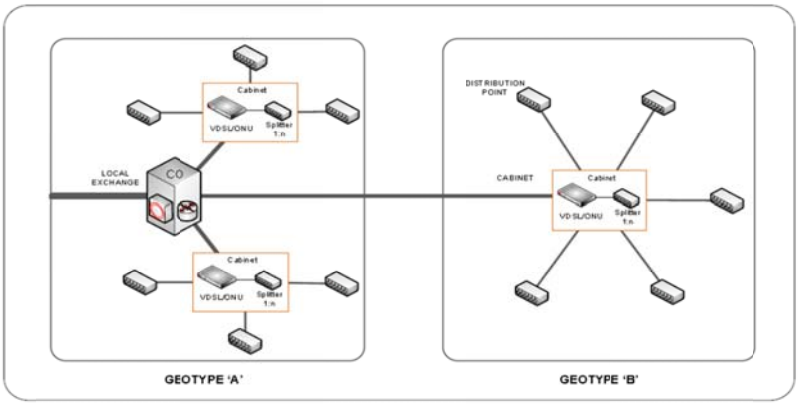

Figure 3.8 – Different geotypes within an access area

To divide the number of potential subscribers (inhabitants, households and businesses) among these two types, 5 prototypical municipalities for each of the zones have been chosen[29]. For each of these municipalities it has been possible to obtain the percentage of surface for dense urban[30] and scattered urban and suburban areas[31] using data from Ministerio de Vivienda (2007). The resulting population-weighted average has been regarded as representative of the situation in each of the zones (see Table Annex.0.4).

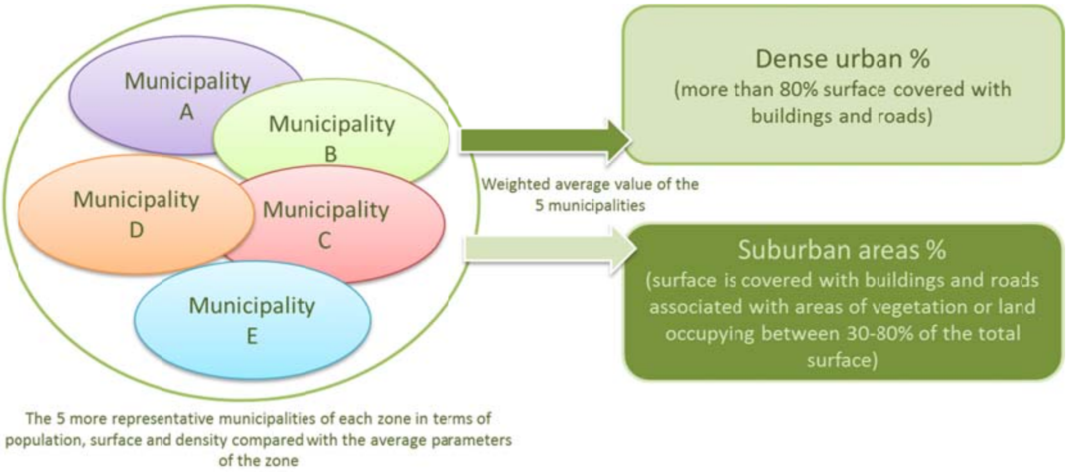

Figure 3.9 – Process description of geotype share calculations in each density zone

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[29] Those municipalities closer to the average population and surface in each zone were selected.

[30] More than 80% of the surface is covered with buildings and roads (IGN, 2000)

[31] The surface is covered with buildings and roads associated with areas of vegetation or land occupying between 30-80% of the total surface (IGN, 2000).

At this point it is important to notice that this approach is valid for a gross estimation. However, in a practical deployment case the optimal trenching topology should be calculated by some –typically heuristic- procedure[32] that takes into account exact data on central offices, location of existing ducts for potential re-use and customer location for each town and municipality.

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[32] For instance, the Steiner tree problem tries to solve the problem of connecting N points to each other with a minimal cost tree structure, see Casier et al (2008).

4. ENERGY CONSUMPTION MODEL FOR THE ACCESS NETWORK

The assessment of energy consumption begins with the selection of the technologies and architectures for the access portion of the network (see section 2.5). These, together with coverage (specific network design) and other quality objectives, determine the number and type of active devices—those consuming energy—in the network. Adding this to a network usage profile along any time period can be used to determine the level of energy consumed in a determined time frame.

In this section, these energy variables, the energy prices, and other parameters for a proper design of the network according to coverage requirements, as well as their reference values, are discussed. According to the parameters here defined and given a particular penetration level, the consumption of a network steady-state can be assessed.

4.1. ENERGY CONSUMPTION OF ACTIVE DEVICES IN THE NETWORK

The calculations of network usage energy consumption are based on the consumption derived from active devices placed within the network.

In fixed architectures, as already stated in section 2.5.1, the two main different types of active devices are the OLT of the Local Exchange, and the ONT placed at the customer premise. In addition to the raw energy consumed for device operation on the local exchange, an extra factor of 60% must be added to the OLT consumption level because of the cooling requirements of the equipment (Bolla et al., 2011; Cucchietti, 2009; Keymile, 2011). The end-user equipment (ONT) cooling factor approaches zero because in this stage, the cooling process occurs in a passive way and therefore does not consume energy (Pande, 2010)[33].

In the PtP architecture no other power consuming devices are placed in between the central office and the premises. On the other hand, in the GPON architecture, one or more distribution points are placed in between these two extremes, splitting the signal and dispensing it among subscribers. These splitters, as passive devices, do not contribute to the energy consumption of the network, but their number does affect the signal power level transmitted to and from the customer premises. Therefore, the energy

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[33] This approach is used for every access network technology analysed.

consumed at the active devices (OLT and CPE) is typically higher than in the PtP architecture (Keymile, 2011).

In the FTTx/VDSL the OLT and CPE power consumption profiles are similar to the FTTH ones, but as the CPEs receive electronic signals instead of optical ones they have different (lower) power requirements. Additionally the Digital Subscriber Line Access Multiplexer (DSLAM) placed at the cabinet, and responsible of converting signals form the optical section of the network into electronic ones (and vice versa), adds consumption to the energy balance (ETSI, 2008; Lastres, Feijóo, Martín, & Martínez, 2010).

In the case of mobile networks, the set of active deployed devices consist of the base stations, the equipment to fill coverage gaps, and the equipment to interface with users' devices. Base stations are the building blocks of any terrestrial wireless deployment, and the footprint of the network is composed of the coverage area of each base station. From an engineering perspective, the network deployment coincides with the selection of the most appropriate location of base stations, given the objectives of coverage and quality of communications (Andrews et al., 2012; Schindler et al., 2011). In general additional equipment is needed to fill coverage gaps due to the existence of physical obstacles to the radio waves emanating from the base stations. This typically occurs in urban areas. There are different types of equipment used depending on the size of the coverage gap; picocells have a coverage radius of hundreds of meters and femtocells tens of meters (Andrews et al., 2012; Ghosh et al., 2012). It is also the objective of both types of equipment to achieve or improve indoor coverage. In this research we will not distinguish between the two types of equipment, and the number of them required for the deployment of the network will be simply a function of the number of buildings in the area and not their size. As an additional simplification, base stations and pico/femtocells are considered in this work as the equipment required for the connection of all types of user devices; not only handsets but also tablets, personal computers or connected television sets, and therefore possible CPE equipment is not considered as such. Wi-Fi traffic off-loading from mobile networks into fixed networks is also considered as explained in the sections below.

For each of these active devices it is necessary to establish an energy profile (see Figure 4.1). These behavioural functions determine the different levels of consumption for the devices according to the workload of the network, based on the model presented in Frenger, Moberg, Malmodin, Jading, and Godor (2011). These profiles are depicted first by a maximum level of consumption of the device (level at 100% work load), and one or two reference levels (this depends on the specific device). In the case of active connecting interfaces like the ones used in the central offices as uplinks for GPON and FTTx/VDSL networks, just a single state of maximum power consumption is defined.

The base station and DSLAM pattern is defined by consumption levels of 100% (high), 50% (medium) and 10% (low or idle) load states, while the profiles of pico/femtocells, OLT and ONT are only defined at the 100% (high) and 10% (low or idle) load states. The low (or idle) state does not coincide with a switch-off power consumption level, as operations other than pure data transmission (i.e., cooling) are necessary at all times. Due to this fact, these devices can never be shut down, even in cases of no transmission, as the reactivation process is not immediate, thus affecting their real-time performance (Frenger et al., 2011).

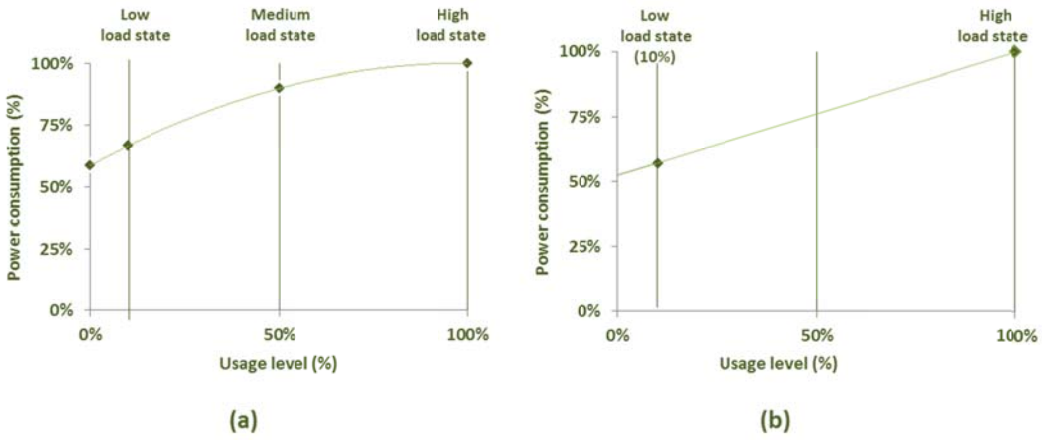

Figure 4.1 –. Quadratic (a) and linear (b) power consumption profiles based on the model from (Frenger et al., 2011)

Table 4.1 – Summary of the different energy profiles features and scope

Profile	*Load states*	*Fixed networks active devices*	*Mobile networks active devices*
Quadratic function profile	High (100%) Medium (50%) Low load state (10%)	DSLAM	Base stations
Linear function profile	High (100%) Idle state (10%)	OLT ONT	Femtocells

The actual energy consumption of the active devices at any given time depends on the data traffic workload (level of usage) of the network. The data traffic pattern in fibre networks has been analysed by Shi et al. (2013), for example, suggesting that an hourly basis is enough to build a reasonable model for dynamic resource allocation.

To avoid the difficulties of a dynamic model, a simpler approach reduces the problem to the consideration of an average hour-by-hour daily traffic evolution. A pattern of average daily usage of a network is presented in Figure 4.2. This pattern was developed within the March Project (CELTIC-Plus, 2011) and is considered representative of the typical daily pattern, encompassing the variations across the different zones where the network is deployed as well as along different time frames of the year (days of the week, months, seasons, etc.). The combination of this pattern with the energy profile already presented permits the determination of the average energy consumed every hour throughout the day by the active devices and thus the daily average and total yearly consumptions.

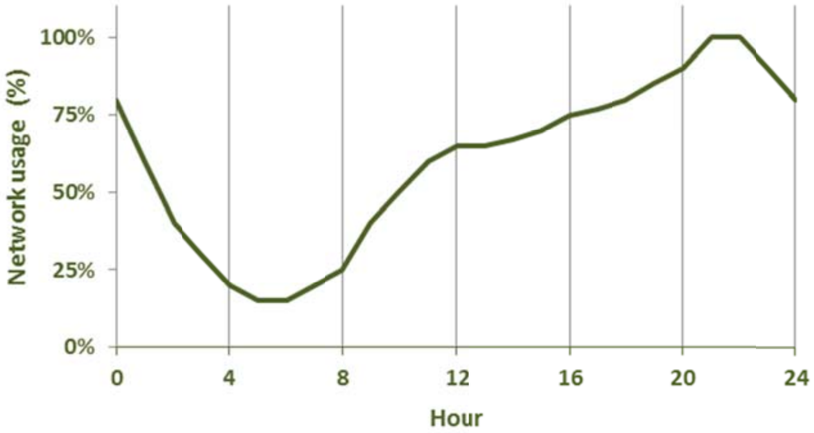

Figure 4.2 – Average daily network usage profile. Source: March Project (CELTIC-Plus, 2011).

4.2. ENERGY PRICES

For cost calculations, the price of the energy was obtained from EUROSTAT data on the electricity prices for industrial consumers in Spain. The price for 2012 was 0.1152 €/KWh. Forecasts of energy prices suggest an increase of 50% by 2030 compared to 2005 levels (EC, 2009, 2010c). This projected increase corresponds to an average annual increase of 2% at constant prices. The complete evolution in the energy prices used for reference is shown in Table 4.2.

Table 4.2 – Annual energy prices reference values

Year	*Energy price (€/KWh)*	*Details*
2012	0.1152	***EUROSTAT electricity prices for industrial consumers in Spain***
2013	0.118	Estimations based on a constant 2% annual increase (with the 2012 value as reference)
2014	0.120	
2015	0.122	
2016	0.125	
2017	0.127	
2018	0.130	
2019	0.132	
2020	0.135	

4.3. NETWORK DESIGN PARAMETERS

According to the usual engineering design approach (Forsgren & Prytz, 2006), the key network parameters are the data traffic per user, the quality of service, the (expected) penetration of each broadband technology, the data throughput (data capacity) of local exchanges and base stations, and (for mobile technologies) the frequency of operation and the amount of spectrum bandwidth allocated to the operator. The sizing of the network depends on all of these parameters and, therefore, so does the energy consumption of the network. Each of these parameters is briefly discussed below, leaving the calculation process for the next section.

Data traffic has undoubtedly experienced significant increases in past years, with global figures up to 43 EB per month in 2012 and a forecasted compounded annual growth rate (CAGR) of 29% for the period 2011–2016, reaching 110 EB/month in 2016 (CISCO, 2012a). Mobile traffic is expected to grow at rates of over 50% until 2020, increasing from 1.3 EB/month in 2012 to approximately 40 EB/month in 2020 (Jefferies, 2011). Mobile traffic off-loaded via Wi-Fi was 9 EB per month in 2012 and is expected to grow to 18 EB per month at a CAGR of 21% (CISCO, 2012a). These figures show how users are changing their habits with regard to broadband, particularly with respect to their increasing usage of data-intensive applications such as social networks, cloud computing and various video services and applications. However, while these figures provide an aggregated average of user behaviour, they do not provide information about their concrete demands at (peak) data rates for specific services and applications. From a technical perspective, GPON technology is expected to be able to provide peak data rates of up to 2.5 Gbps, PtP goes as far as 40 Gbps, FTTx/VDSL has a modest (compared with the other fixed technologies) peak value of 300 Mbps, and expected LTE peak data rates range up to 150 Mbps. These figures seem well above current prospects of (peak) user behaviour, whatever the combination of advanced services and applications they choose, and they are also well above main policy objectives set in the range of 100 Mbps for 2020 (EC, 2010a).

In between average and peak data rates, the amount of time a given data rate is guaranteed for users –or alternatively the number of users than can be served simultaneously at a given data rate- is specified by the quality of service (QoS). In fact, QoS is arguably the design parameter that most affects the deployment of a network and, therefore, its energy consumption. While QoS levels are currently considered to be low, especially in mobile networks (Ixia, 2011; Vadada, 2010), it is expected that the evolution in the demand of higher speeds will be in accordance with an increase in the standards of QoS offered to users. Here, the starting point for the guaranteed data rate per subscriber is established initially at 30 Mbps in fixed networks and 1 Mbps in mobile networks. These are reference values for each technology that cover the current needs for more demanding data applications (Jukan & Mambretti, 2012; Radio, Ying, Tatipamula, & Madisetti, 2012).

Broadband penetration determines both the total number of potential subscribers and, along with the demographic scenario and the network deployment strategy, the number of them located in each area—the objective of the deployment. The fixed broadband penetration in January 2012 was 81.1% of the premises, on average, in the EU (EC, 2012). Of this value, only 7.2% of the lines provide speeds of 30 Mbps or above. A typical target for the prospective market saturation level of fixed broadband technology is set at 80% penetration in premises (Analysys Mason, 2008). As for mobile technologies, while the level of adoption of mobile services in general is over 100% in most developed countries, the specific penetration of mobile broadband (3G and beyond) is still relatively low: 43% in January 2012 (EC, 2012). Most market prospects assign 4G figures approaching 80% of the population by 2020 (Jefferies, 2011). Once the number of potential subscribers is determined, an operator can follow different strategies for the deployment of the network, essentially using different combinations for the number of users in different areas to achieve an overall target. In general, as deployment costs per user are inversely related to population density (Tselekounis, Maniadakis, & Varoutas, 2012), the most rational strategy for the operator to follow would be to start the deployment in those areas with higher population densities. Note that this is not always the case, primarily as a consequence of diverse types of regulatory conditions.

The data throughput of a FTTH-GPON local exchange is dependent on the number of OLT cards and the splitting ratio in the GPON architecture. Here, a conservative scheme of two levels of splitting -8x8- has been preferred (Analysys Mason, 2008; Bock et al., 2008). This implies that each feeder fibre from the local exchange serves 64 customers supplying a maximum data rate per user of 30 Mbps downstream and 19.5 Mbps upstream. Higher data rates require the replacement of OLT cards and splitters to work with 10 Gbps feeder fibres, the next step in GPON technology. In extreme rural areas a lower splitting ratio has been used due to the reduced number of potential subscribers. The main figures on coverage for all the fixed technologies[34] selected are presented in Table 4.3.

Table 4.3 – Fixed networks sizing

Zone	*I*	*II*	*III*	*IV*	*V*	*VI*	*VII*	*VIII*	*IX*	*X*
Number of users per access area	16,384	16,384	16,384	16,384	16,384	16,384	4,096	2,048	512	256
Minimum number of fibres at the exchange	256	256	256	256	256	256	64	32	8	8
Total splitter ratio	8x8	8x8	8x8	8x8	8x8	8x8	8x8	8x8	1x8	1x4
Number of users served by a cabinet	512	512	512	512	512	512	256	128	128	64
Number of cabinets	32	32	32	32	32	32	16	16	4	4

In the case of mobile networks, frequencies allocated to the operator impact both the coverage and maximum throughput (the total data capacity) of each base station; the lower is the frequency of operation the greater is the coverage, and the higher is the bandwidth, the higher is the throughput of the base station. Base station coverage is delimited by the lesser of two factors. The first is the share of the maximum throughput among the users while complying with QoS requisites. This limitation varies inversely with population density. The second derives from signal transmission losses; beyond a certain distance, the signal is compromised with excessive errors. A typical maximum coverage radius at mobile communications lower frequencies ranges up to 50 km (Astely et al., 2009; Furuskar, Jing, Blomgren, & Skillermark, 2011). However, this value diminishes to just a few km in areas of high building clustering or complex orography, where the combination of diffraction and multipath interference significantly

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[34] Splitting factors do not apply for FTTH-PtP networks and the number of cabinets are only used for FTTx/VDSL.

increases signal losses and errors. In any case for mobile broadband, the first limiting factor occurs usually in high (urban) and medium (suburban) population density zones, while the latter is typical of low population density zones (rural). As a consequence of the above, lower frequencies of operation (such as those resulting from the digital dividend) do not increase network coverage if the limiting factor is QoS.

The data throughput of a mobile base station depends, in addition to the bandwidth allocated to the operator, on the spectral efficiency level and on vendor-dependent parameters, such as number of sectors and number of channels for data transmission. Bandwidth allocation is subject to regulatory constraints due to the scarcity of the spectrum in more convenient frequency bands. In LTE technology, a typical value for this parameter is currently 20 MHz (Etemad, 2008; IDATE, 2012), although higher values will be required to satisfy the increasing demands of users as discussed in the next section. The spectral efficiency determines the capacity of using each unit of frequency available in the allocated bandwidth to transmit at a specific data rate. It is measured in bits per second per Hertz. A typical peak value for this parameter in LTE is 15 bps/Hz (Etemad, 2008; IDATE, 2012), achieved in the proximity of base stations. As it is supposed a very dense cellular network it is used as a reference value. The number of channels and sectors refers to the configuration on base stations. A typical LTE configuration features 3 sectors (each covering a 120º angle) and a 2x2 MIMO[35] (the one used in this model) or a 4x4 MIMO (Margot Deruyck, Tanghe, Joseph, & Martens, 2011) channel configuration. Considering the above parameters, a baseline base station could manage a total data throughput of up to 1,800 Mbps.

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[35] MIMO (Multiple Input Multiple Output) is a technology that makes use of antenna arrays with smart signal-processing algorithms at both the transmitter and receiver to improve communication performance. The notation IxO (i.e. 2x2, 4x4) determines the number of input and output radio channels carrying the signal, not the physical antenna devices.

5. BASELINE

5.1. CALCULATION PROCESS

Once all the elements needed have been introduced, the next sub-section presents a detailed description of the full calculation procedure, explaining the influence of each parameter. This process is designed "from the bottom up", following the traditional engineering design approach (Forsgren & Prytz, 2006), and consists of two main parts. The first determines the size—the coverage footprint—of the basic coverage unit for each technology (the local exchange access area for fixed networks and cell for mobile networks) and the number of them needed in the different zones that compose the demographic scenario. In the second part, the per-hour average, daily average and yearly energy consumption of the access network are determined by applying the energy profiles of the active devices combined with the network usage pattern.

Nevertheless before starting the thorough explanation of the process some singularities regarding the coverage assessment process have to be explained. In an ideal scenario where each density zone has continuity and homogeneity no corrections to the network sizing would be required. However for a scenario closer to reality, information on the population granularity of the municipality is required. Two different considerations must therefore be made:

- *Intermunicipality correction*: Compensates the lack of continuity across municipalities within a specific density zone.
- *Intramunicipality correction*: Compensates the scattering of premises in a given municipality.

The first effect is due to the lack of continuity of the different municipalities that fall in each one of the ten density zones. As these municipalities might be scattered along the Spanish scenario, for calculation purposes the figures regarding coverage requirements of each zone cannot be taken as if the customers were grouped all together (see Figure 5.1).

To correct this effect, a complete access network has to be deployed in each municipality, even if the remaining population of the access network is lower than the total capacity of the access network. This correction is equivalent to extract each municipality in the zone and calculate the required number of cells to cover it and then round this number up to the nearest integer to cater to the remaining fraction of users not covered (the worst-case design)

In the cases when the total number of network units to be deployed to cope with the demand is lower than the number of municipalities covered given the demand, the number of network units required will be the number of municipalities. On the other hand, when the number of network units is over the total municipalities, to correct the effect a number equal to the total number of municipalities covered minus one network units have to be added to the calculated networks to be deployed.

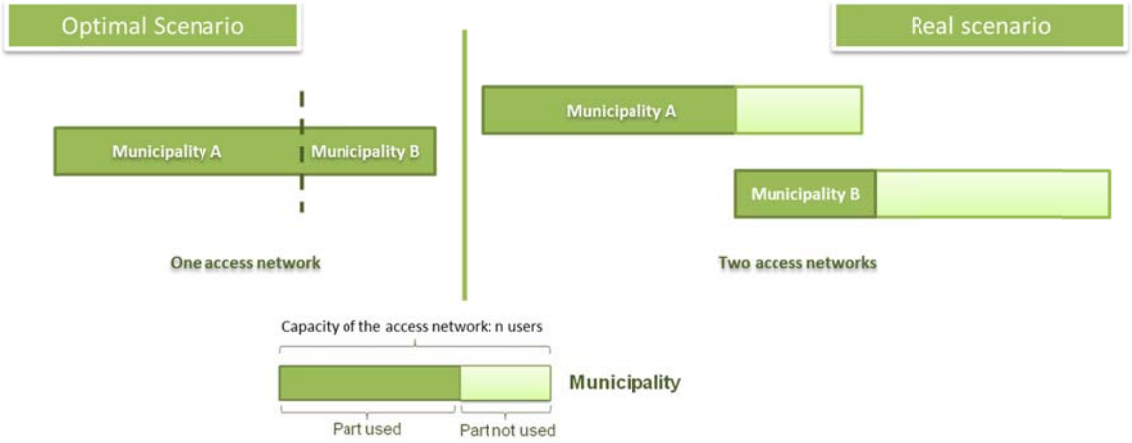

Figure 5.1 – Schematic explanation of the intermunicipality correction factor

The intramunicipality correction is only made in mobile networks as the radio is a limiting factor. It is typical of very low population density zones and occurs in municipalities where two conditions are fulfilled: first the population of the municipality is lower than the number of user per cell, and second the surface of the municipality is greater than the area covered by the cell

In these cases the number of total additional cells and base station per area is equivalent to the round up number derived from the division of the municipality surface between the specific coverage area of the cell in each density zone.

5.1.1.FIXED NETWORKS

The starting point of the calculation process is the number of potential subscribers covered by a local exchange. As the location of local exchanges is re-used from legacy networks, this value is already set, as indicated in the first row of Table 4.3.

The second part of the calculation process considers the power required by the active devices in the network.

In PtP networks, as mentioned before, it is only necessary to operate the laser diodes that deliver information to the users subscribed to the network service. The number of local exchange offices (and therefore of OLT) will depend directly on the number of interfaces required. The extra cooling factor must be added to the interface own consumption.

$$P_{LE} = P_{OLT} + P_{cooling} = P_{OLT} \times \left(1 + \alpha_{cooling}\right) = P_{OLT}(1 + 0.6) \qquad \textbf{Eq. 1}$$

Consumption at the ONT is described by the reference values in (EC, 2011). In GPON networks, the ONT requires higher power to operate due to the loss in splitters (Keymile, 2011).

In GPON, for the central office configuration, uplinks and downlinks have to be considered to assess the consumption, according to the premises covered. Each of these interfaces has different energy consumption values. Uplink consumption level has a fixed value while downlink value varies attending to the consumption profile presented in 4.1.

$$\begin{aligned} P_{OLT} &= \left(P_{Uplink} + P_{Downlink}\right) + P_{cooling} = \\ &= \left(n_{up} \times p_{uplink} + n_{down} \times p_{downlink}\right) \times \left(1 + \alpha_{cooling}\right) \end{aligned} \qquad \textbf{Eq. 2}$$

In FTTx/VDSL networks, the consumption for this technology due to the OLT is equal to the one calculated for the GPON network, and the one due to the CPE (ONT) is different as this device receives electrical signals instead of optical ones. The cabinet consumption is set at the value per interface needed for each user served by the cabinet (see Table 4.3).

Once obtained the number of access areas and energy consumption of the active devices required, by dividing the number of subscribers between the number of users per access area, the hourly energy consumption calculation for each access area and for the complete density zone can be performed as depicted in Figure 5.2

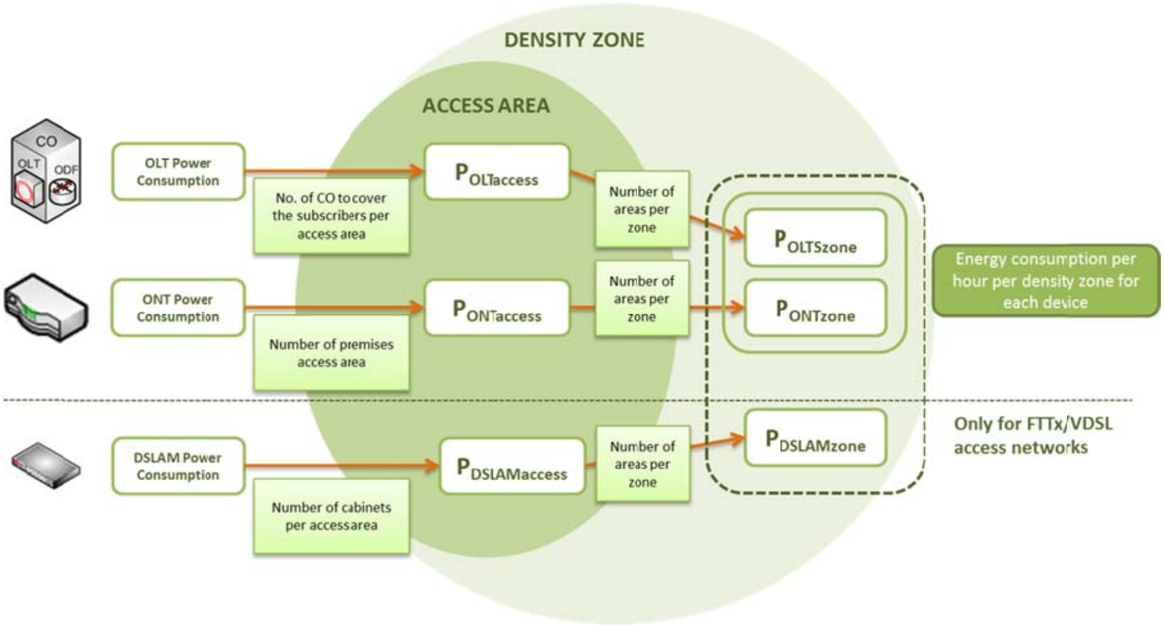

Figure 5.2 – Fixed networks hourly energy consumption calculation process

The combination of the energy profile of the devices with the network daily usage pattern allows for obtaining the percentage of power consumption regarding the maximum of each device for every hour of the day and its aggregation derives in the daily and annual consumption for the complete demographic scenario (see Figure 5.3[36]). Energy consumption calculations for fixed and mobile access networks show their primary differences in the first part of the process. This second stage of the procedure is common for both types of networks, with the exception of using the appropriate device energy profile in each case.

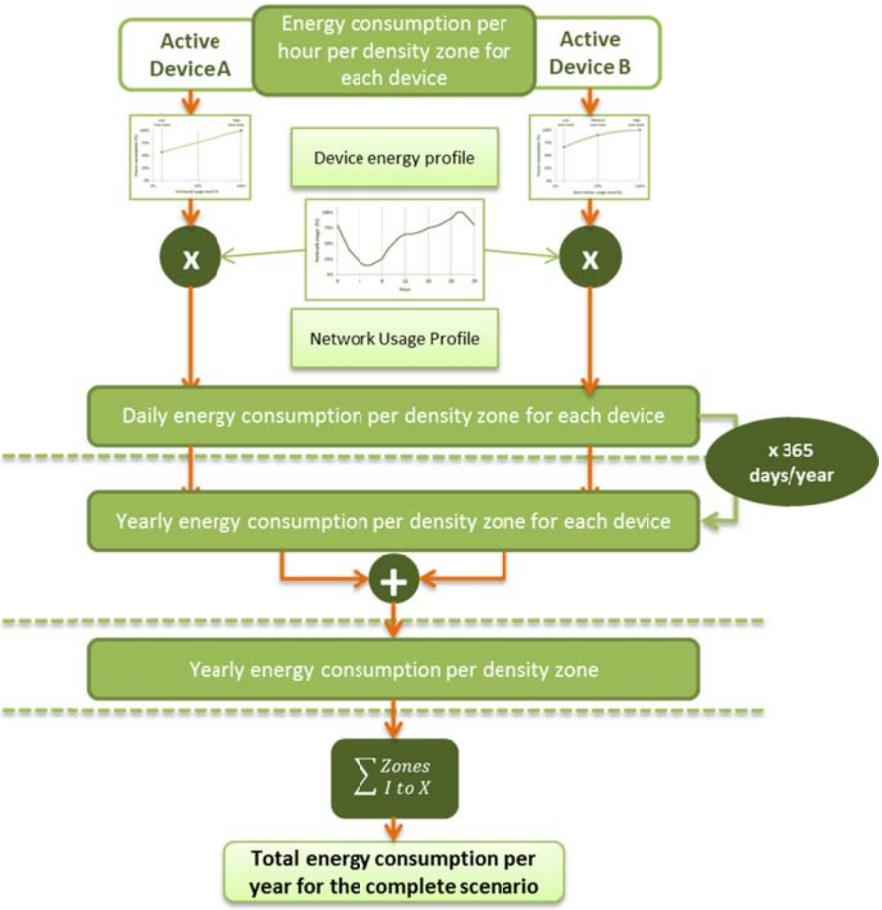

Figure 5.3 – Access network daily and annual energy consumption calculation process

5.1.2.MOBILE NETWORKS

With mobile networks, calculation procedure begins at assessing the size of the cell, both in terms of the area covered and maximum number of subscribers (see Eq. 3). The latter is simply calculated from the relationship between the total data throughput per base station and the specified QoS.

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[36] The number of active devices at the top of the figure depends on the specific architecture of the access network and therefore there can be three instead of two as depicted in the figure.

$$n_{users} = \frac{Total\ Data\ Throughpput}{QoS\ (data\ rate\ per\ user} = \frac{BW \times Spectral\ Efficiency \times n_{sectors} \times n_{antennas}}{QoS} \qquad \textbf{Eq. 3}$$

This maximum number of subscribers is then compared with the size of the municipality. If it is lower, then the size of the cell is calculated as the size of the area covering that number of subscribers, given the population density of the zone under consideration. The number of cells in the municipality is rounded up to the nearest integer to cater to the remaining fraction of users not covered (the worst-case design). On the contrary, if the maximum number of subscribers is greater than the population of the municipality, then it will be limited by the population of the municipality, and the cell size is the maximum range of coverage at the frequency of operation. If the range of the cell is smaller than the size of the municipality, then the location of premises in the municipality is used to check the required number of cells (due to the correction factor previously explained). If the range of the cell is greater than the size of the municipality and there are no geographic obstacles (a rare situation in Spain), then the population of the neighbouring municipality is also considered for cell coverage. Although this simplified process may slightly over-estimate the number of base stations required, it also reflects the reality concerning licenses for base station sites, usually granted at the municipal level. It is therefore considered a reasonable depiction of a real deployment situation for mobile networks.

Table 5.1 presents the resulting number of potential subscribers per base station across the different demographic zones[37]. The number of femtocells per cell is also obtained at this stage from the percentage of urban buildings with respect to the total number of premises in the average municipality in the zone.

Table 5.1 – Mobile access network sizing.

Zone	*I*	*II*	*III*	*IV*	*V*	*VI*	*VII*	*VIII*	*IX*	*X*	*Total*
Number of cells	7,376	17,185	10,487	23,542	13,870	31,765	10,884	15,202	3,973	4,218	***42,105***
Number of users per cell ($n_{usercell}$)	360	360	360	360	360	360	360	360	223	106	
Area of the cell	0.05	0.15	0.24	0.59	1.41	4.56	14.28	36.71	64.36	60.42	
Radius of the cell	0.13	0.22	0.27	0.43	0.67	1.21	2.13	3.42	4.53	4.39	
Number of areas per zone	160	373	227	508	297	670	845	2083	1265	1,199	***7,627***
Number of users per area	16,384	16,384	16,384	16,384	16,384	16,384	4,096	2,048	512	256	
Number of cells per access area	46.10	46.07	46.20	46.34	46.70	47.41	12.88	7.30	3.14	3.52	

In the case of mobile networks, an access area is also calculated. The reason for adding this intermediate stage in the calculations for the deployment of a mobile network derives from the interest in establishing a common framework for comparisons between mobile and fibre-based technologies with respect to the access part of the

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[37] For the baseline scenario, if the QoS condition vary along the deployment this figures would be also modified. This will note be the case in fixed network sizing as in that case the sizing parameters are constant independently of these conditions.

network. Note that base station topology is denser than that of local exchanges (their fibre-based "counterpart"), and thus, to effectively reach subscribers, it is necessary to lay a certain amount of fibre (Figure 2.8 in section 2.5.3Figure 2.8) from where an equivalent local exchange would be located. Therefore, using this fictitious "access area" permits the calculation of the additional fibre (the "middle mile") that must be deployed to reach the base stations in a mobile network. Thus, the inclusion of this value in the cost and energy calculations of the mobile access network creates a framework that is more comparable with fixed technologies.

The maximum energy reference level of pico/femtocells is constant through the demographic scenario. This value defines the power required by the customer premise equipment placed at each building of the geotype a of each density zone (see Table Annex.0.4).

However, in the case of base stations, this level varies with the number of subscribers and therefore changes across zones due to the energy consumption calculation used for base stations (Eq. 4). The model is based on the base station architecture (see Figure 5.4) described in M. Deruyck et al. (2010a) and M. Deruyck et al. (2010b).

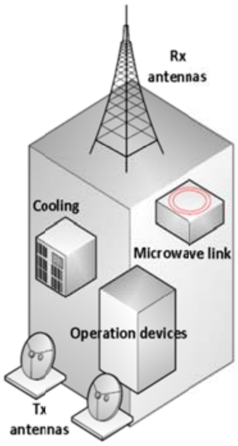

Figure 5.4 – Base Station architecture

$$P_{BS} = P_{BaseStation} + P_{cooling} + (n_{antennas} \times P_{MWlink} \times \eta_{MWlink}) \qquad \textbf{Eq. 4}$$

Where (see Table 5.2 for details on the reference values):

- $P_{BaseStation}$ includes all the energy consumption required for the reception, processing and transmission of information, including, the power consumed by the optic fibre connection to the base station if required.
- $P_{Cooling}$ includes all the energy consumption to keep temperature of base station within the appropriate range.
- $n_{antennas}$ is the number of antennas used in the base station configuration selected.

- $\boldsymbol{P_{MWlink}}$ includes the power required to operate the microwave links used to connect to the backbone networks (if exist)
- $\boldsymbol{\eta_{MWlink}}$ is the percentage of base stations with microwave links in each density zone. It is assumed that microwave links will be used only in geotype b (in geotype a optic fibre will be used to connect with the backhaul so the energy consumption involved is already included in the $\boldsymbol{P_{BaseStation}}$).See Table Annex.0.4.

Table 5.2 – Base station power consumption model reference values

Section	***Reference value***
$P_{BaseStation}$ (W) ***(EC 2011)***	1,200[38]
$P_{Cooling}$ (W) ***(Deruyck et al. 2010)***	690
P_{MWlink} (W) ***(EC 2011)***	20
$n_{antennas}$	2

The complete process for the hourly energy consumption calculation for each device in the mobile access network is depicted in Figure 5.5.

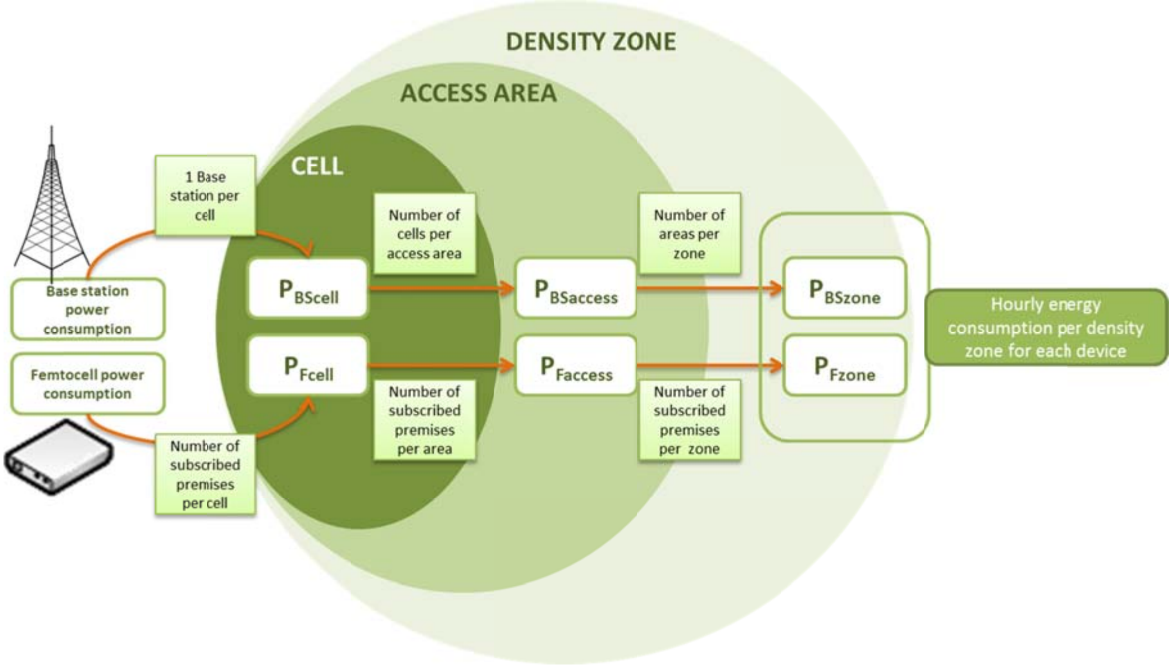

Figure 5.5 – Mobile networks hourly energy consumption calculation process

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[38] Reference value in EC (2011) for 2011. This value varies along the deployment period. See section 5.3.1 for details.

Again, the second stage of the calculation process (see Figure 5.3) allows obtaining daily and yearly figures on the energy consumption, applying the adequate device consumption profile along with the network usage pattern.

5.2. ENERGY COST CALCULATIONS

The use of the energy resources derive necessarily in an economic cost reflected in the expense balance of the network operator. The cost implied echoes in the operating expenses, which are in fact of great importance in order to determine the economic viability in the long term of the deployment project. While the capital expenditure required for the rolling-out has to be undertaken during the deployment period, the operating expenses have to be confronted along the complete life cycle of the network. Therefore a proper network design, enhanced with energy efficiency processes will derive in a lower economic impact.

Next figure shows the process of assessing the cost related to the annual energy consumption calculated. The energy price and its evolution along the deployment period analysed was already presented in section 4.2.

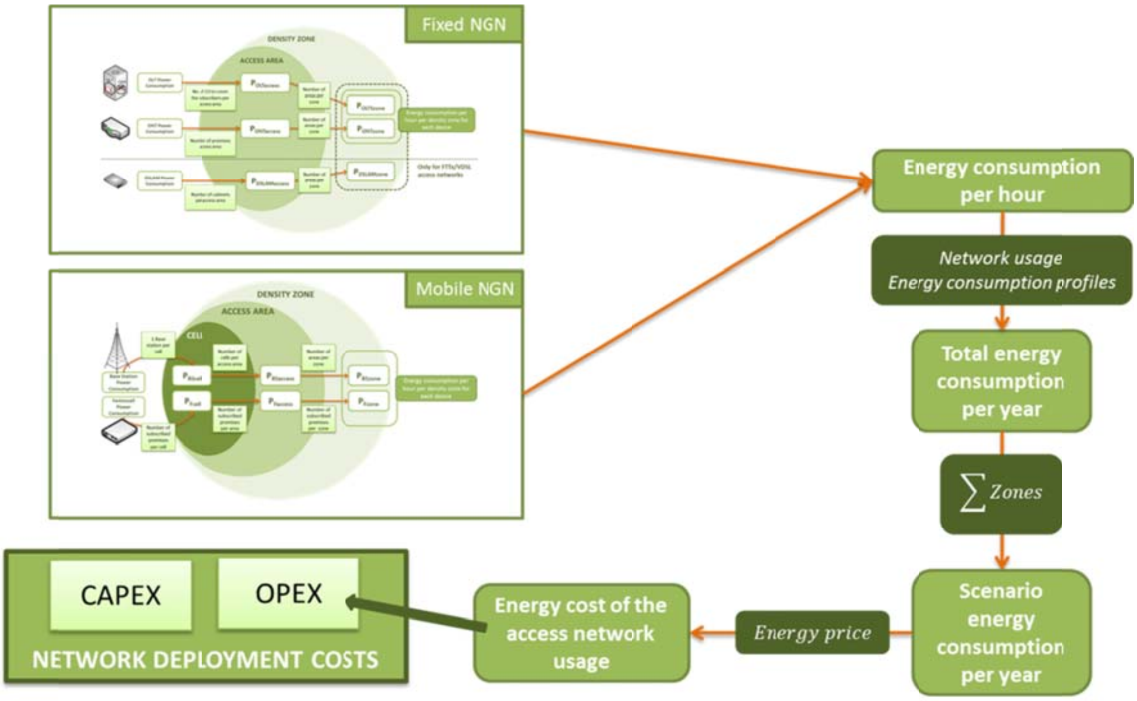

Figure 5.6 – Energy cost calculation complete procedure

5.3. EVOLUTION ALONG THE NETWORK DEPLOYMENT

Energy consumption of NGNs in the 2020 horizon depends on the evolution of some of the variables described in the previous sections. As a consequence of these changes in the reference value of the parameters used, the levels of energy consumption in a broadband network display a significant change along this future timeframe.

Therefore the process described for each technology evolves towards assessing the evolution over time of energy consumption levels along the deployment period proposed.

These variations may be caused by a combination of many different factors. Therefore, the research offers in particular a middle-term projection considering the evolution of technologies, the increasing energy efficiency of devices, user demands and devices (their combination reflected in data traffic), the penetration of each technology, the effects of the deployment progress of the networks, and the evolution of energy prices[39]. Four different methodologies are combined to obtain this baseline for forecasting: the technological perspective for the consumption of active devices, a techno-economic scenario to construct data traffic patterns, growth curves for mobile technology penetration, and strategic scenarios for the deployment of the network.

In the following sub-sections the evolution over time of each of these parameters is considered in some detail.

5.3.1. TIME EVOLUTION OF THE ENERGY CONSUMPTION OF ACTIVE DEVICES

There are three main and mutually compatible ways of increasing the energy efficiency of networks with respect to the active devices. The first would be an architecture design aimed at reducing energy requirements. However, this is seldom the case, as network architectures are usually designed to fulfil specific coverage and service provision goals (Cuomo, Cianfrani, Polverini, & Mangione, 2012). The second set of possible enhancements takes place at the system and network levels, in the definition of new functions, network management mechanisms and algorithms for dynamic resource management. These features are typically implemented at the software level and potentially upgraded and introduced in the network over the lifetime of several hardware generations. These potential improvements can be achieved, for instance, by using techniques to manage discontinuous transmission time slots during device operation (Frenger et al., 2011) or by analysing the network requirements and training the network to respond dynamically, putting specific sections to sleep (Cuomo et al., 2012; Shi et al., 2013). The third and most evident possibility is implemented at the device level, using the most up-to-date energy-efficient equipment either for new deployment or for replacement of existing equipment once the hardware amortization has taken place. Technically, to achieve higher efficiency, the energy consumption profiles are modified by lowering the level of power consumption at the 100% load state (maximum power consumption in absolute terms) or by adjusting the relative variation of the other states with respect to the maximum level of consumption. In this paper, both possibilities are combined in the suggested evolution for these patterns.

In the forecasting exercise here presented, only the last approach is considered in the baseline, as it is by far the most common procedure. Therefore, the most energy-efficient devices are included in the network deployment on a yearly basis. The devices

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[39] The evolution of energy prices only impacts on the year-to-year energy cost calculation. The assumptions made are based on industry predictions regarding a reference value for the price of energy obtained from EUROSTAT, and have been described already in section 4.2

already deployed are only replaced for more efficient ones after five years, which is the period assumed for device amortization. The only exception takes place from 2017 onwards on mobile networks, where variations on the key design features of the network require a general replacement with new devices[40].

The evolution of energy consumption in network devices extrapolates existing guidelines for the short term (EC, 2011; ETSI, 2009), where the improvement in energy efficiency performance translates into a modification of the energy profile. In this sense, the change affects both the maximum energy consumed and the percentage of this value consumed at each load state. The evolutions assumed for each device energy consumption profile as well as the reference values are now summarised in next tables and figures

Table 5.3 – Evolution figures for bases stations used in LTE access networks

Year	*Full load state (Wh)*	*Meduium load state (Wh)*	*%*	*Low load state*	*%*
2011	1,200	1,080	90%	900	75%
2012	1,100	950	86%	750	68%
2013	900	750	83%	550	61%
2014	800	632	79%	432	54%
2015	750	570	76%	353	47%
2016	700	504	72%	280	40%
2018	1000	690	69%	330	33%
2020	900	585	65%	234	26%

Table 5.4 – Evolution figures for femtocells used in LTE access networks

Year	*On state (Wh)*	*Idle state (Wh)*	*%*
2011	8.0	7.0	88%
2012	7.0	6.0	86%
2013	7.0	6.0	86%
2014	6.1	5.1	84%
2015	6.1	5.1	84%
2016	5.4	4.4	82%
2018	5.4	4.4	82%
2020	4.7	3.8	81%

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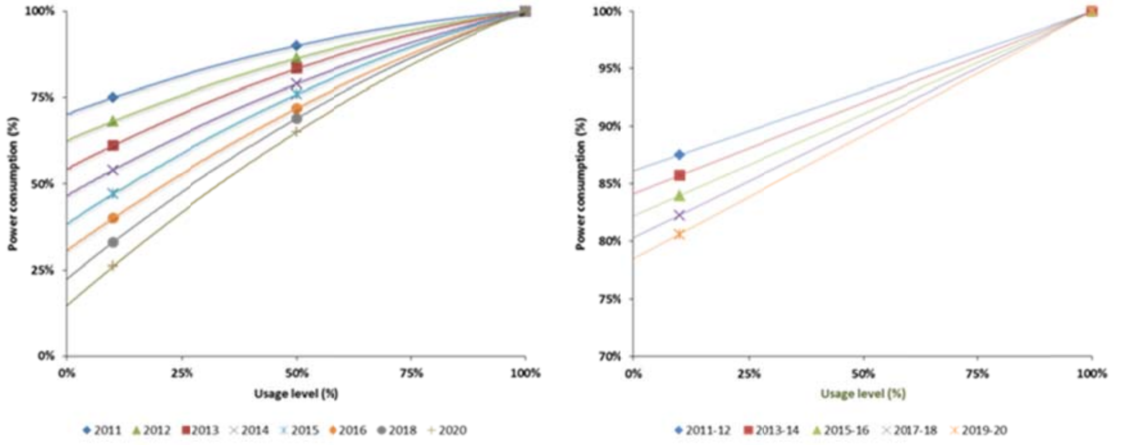
[40] See next sub-section for a detailed explanation of these changes



(a) (b)

Figure 5.7 – Energy consumption profiles for LTE active devices: (a) base stations; (b) femtocells

Table 5.5 – Evolution figures for ONT and OLT used in FTTH-PtP access networks

Year	*OLT*	*ONT*
	On state (Wh)	*On state (Wh)*
2011	4.5	3.5
2012	4.5	3.5
2013	4.0	3.2
2014	4.0	3.2
2015	3.5	2.9
2016	3.5	2.9
2018	3.1	2.6
2020	2.7	2.4

Table 5.6 – Evolution figures for OLT used in FTTH-GPON access networks

Year	*Downlink*	*Uplink*
	On state (Wh)	*On state (Wh)*
2011	19.0	9
2012	16.0	
2013	14.0	
2014	12.5	
2015	11.3	
2016	10.3	
2018	9.5	
2020	9.0	

Table 5.7 – Evolution figures for ONT used in FTTH-GPON access networks

Year	*On state (Wh)*	*Idle state (Wh)*	*%*
2011	7.9	4.6	58%
2012	7.9	4.6	58%
2013	7.0	4.3	61%
2014	7.0	4.3	61%
2015	6.1	4.0	66%
2016	6.1	4.0	66%
2018	5.5	3.7	67%
2020	4.9	3.4	69%

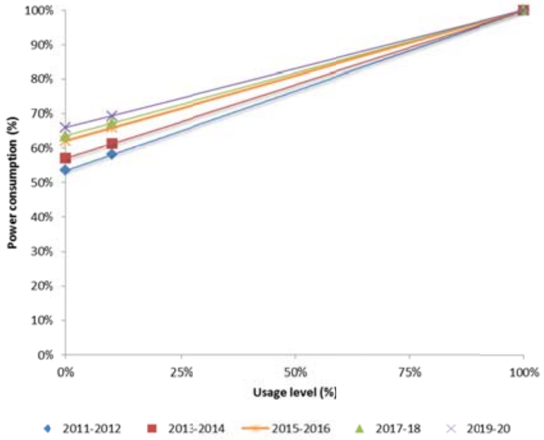


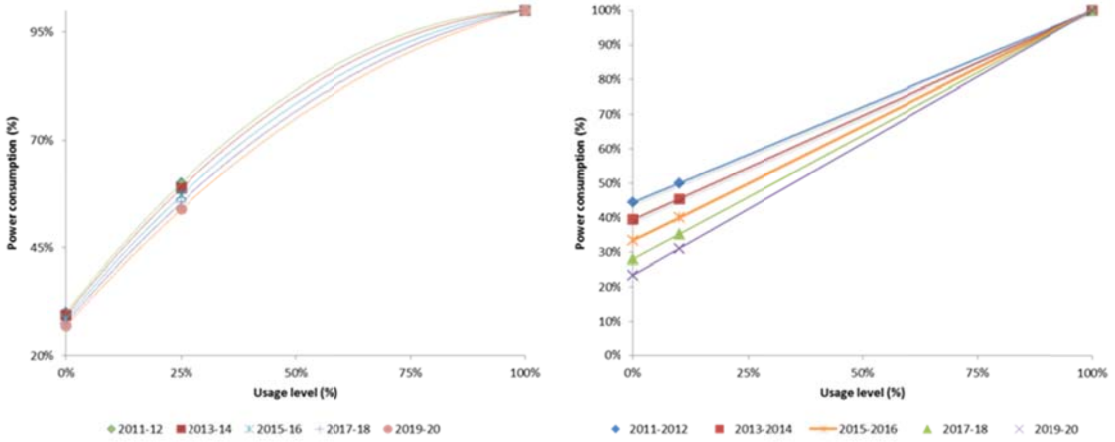
Figure 5.8 – Energy consumption profiles for ONT FTTH-GPON active devices

Table 5.8 – Evolution figures for DLSM used in FTTX/VDSL access networks

Year	*Full load state (Wh)*	*Meduium load state (Wh)*	*%*	*Low load state*	*%*
2011	2.0	1.2	60%	0.6	30%
2012	2.0	1.2	60%	0.6	30%
2013	1.7	1.0	59%	0.5	29%
2014	1.7	1.0	59%	0.5	29%
2015	1.4	0.8	57%	0.4	29%
2016	1.4	0.8	57%	0.4	29%
2018	1.2	0.6	56%	0.3	28%
2020	1.2	0.6	56%	0.3	28%

Table 5.9 – Evolution figures for CPE used in FTTX/VDSL access networks

Year	*On state (Wh)*	*Idle state (Wh)*	*%*
2011	15.00	7.50	50%
2012	15.00	7.50	50%
2013	11.00	5.00	45%
2014	11.00	5.00	45%
2015	8.00	3.20	40%
2016	8.00	3.20	40%
2018	5.82	2.05	35%
2020	4.23	1.31	31%



(a) **(b)**

Figure 5.9 – Energy consumption profiles for FTTx/VDSL active devices: (a) DSLAM; (b) CPE

5.3.2. TIME EVOLUTION OF DATA TRAFFIC PER SUBSCRIBER

Regarding data traffic, an increment of guaranteed speeds is considered, in accordance with the increasing prevalence of broadband-intensive applications such as video, cloud computing, videogames, and—in the mobile domain—M2M and augmented reality. The objective figures for 2020 are set at 100 Mbps for fixed networks and 5 Mbps for mobile networks, in conjunction with policy (EC, 2010a) and current industrial perspectives (Jukan & Mambretti, 2012; Radio et al., 2012). In particular, in fixed networks, the guaranteed data rate is assumed to increase from 30 Mbps to 50 Mbps by 2016 and to 100 Mbps by 2020. In mobile networks, a more nuanced evolution is assumed to take place, from 1 Mbps to 2 Mbps in 2013, to 3 Mbps by 2015, and to 5 Mbps by 2017. The corresponding CAGR of the guaranteed data rate for the period 2011–2020 for fixed networks is 13%, while for mobile networks it is 17%. Both figures are rather more conservative than the forecasts of aggregated data traffic growth used as reference (CISCO, 2011b, 2012a, 2012b; Jefferies, 2011).

Note that, for mobile networks, the achievement of these objectives requires a shift in two key design factors: spectral efficiency and allocated spectrum. Expecting a similar evolution from 3.5G to 4G technologies (Lluch, 2012) a shift from 15 to 20 bps/Hz is proposed for spectral efficiency. Regarding allocated spectrum to operators, a move from the initial 20 MHz to 40 MHz is also proposed. Both network design enhancements are assumed to take place in the year 2017. This is in line with expectations in the availability of new spectrum set in EU and US policies (Commission, 2010). In the case of fixed networks, the objectives set in the baseline would require to change the OLTs to increase the capacity provided by the feeder optic fibres in 2020.

As mentioned in previous sections, the network energy consumption levels are highly dependent on the data rates per subscriber. To determine the evolution of this parameter, a scenario for the average user behaviour and a threshold for the operator's assignment of the quality levels are needed. This is the usual procedure in the design of future networks, although the results are subject to considerable uncertainties and are usually adapted over time to changing market conditions[41]. A simple approach is proposed below, in line with the aim of this work of creating a framework for energy consumption forecasting in NGANs. Figure 5.10 summarises the approach that is described in the following paragraphs.

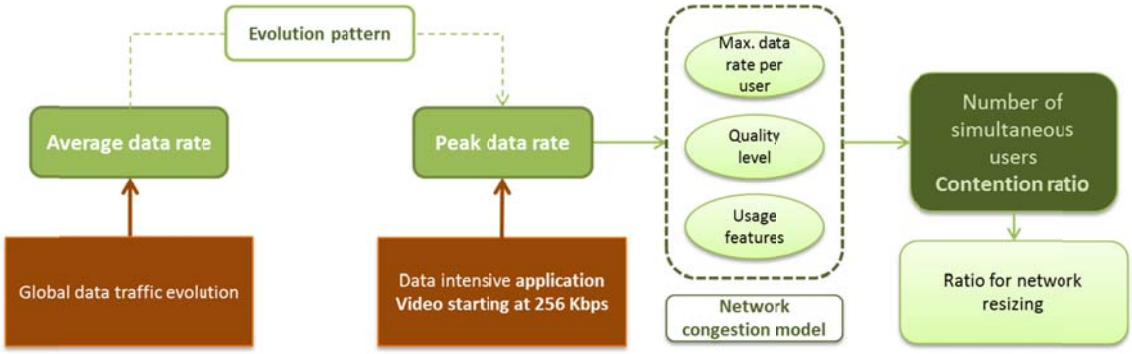


Figure 5.10 – Network congestion model

The first step in the approach is to determine the mobile data traffic evolution using existing data and predictions by industry sources (CISCO, 2011b, 2012a, 2012b; Jefferies, 2011). The combined data are used to obtain the evolution of the total mobile data generated by subscribers over a particular time period, typically a month. For a known number of subscribers in the network, the total data rate can easily be transformed into an average data rate per subscriber[42]. However, average data rates and their evolution profiles are not sufficient because the design of the network requires a worst-case scenario, that is, the calculation of the maximum data rate that would be available for users.

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[41] The scalability of mobile networks facilitates this adaptation, which is a primary difference from fixed networks.

[42] Note that the average data rate per subscriber is only a percentage of the maximum technologically available rate, because the total data throughput from the base station in this type of network is shared by the subscribers that are using the network at a given moment.

For the worst-case scenario, the data rate requirements of services are first determined. As previously explained, this procedure is typically used to calculate the future performance of networks (see for instance ITU (ITU, 2000, 2006)). While there are many services of interest[43], those that require the highest data rates in the mobile domain are cloud computing, enhanced video, advanced gaming and augmented reality (Feijóo, 2013, forthcoming). Cloud computing demands high data rates because of the need to access to massive storage facilities. The other three services all require very high video resolution. Experts consider high-resolution video to be the more resources demanding application (Radio et al., 2012). Table 5.10 shows the proposed evolution of the mobile usage scenarios over the investigated period, both qualitatively and quantitatively. These scenarios were developed from a literature review[44].

The next step in the model is the so-called "network congestion model". In this model, the number of simultaneous users within a cell and the probability of these users accessing network resources are considered (Jukan & Mambretti, 2012; Radio et al., 2012). At low data rates, all the users within a cell coverage area receive adequate service, subject to the propagation conditions. At higher data rates, fewer users can be adequately served by each base station, and more base stations are needed to maintain the quality levels. The total power consumption rapidly increases at higher traffic levels. Obviously, the probability of several users using the resources of the network at the same time depends on diverse application usage factors, such as the probability of daily usage, the hours of access of major users, and the average length of the usage sessions. These factors are used in the following series of equations to obtain the number of users that can use the network resources for a given QoS. This number is usually expressed as a contention ratio 1: m, that is, the number of users m that equal one user who is fully accessing the network resources. Table 5.11 shows the data rate for the most resource demanding application, the guaranteed data rates per subscriber and the contention ratio.

$$P_1 = \frac{p_{day} \times l_{usage}}{t_{session}}$$ **Eq. 5**

$$n = \frac{V_{user}}{V_{app}}$$ **Eq. 6**

$$P_n = {P_1}^n$$ **Eq. 7**

Start with $P_m = c(m, n) \times P_n$, m=0, 1, 2, 3… and continue until $1 - P_m < QoS$: the higher m value that satisfies the condition determines the contention ratio. **Eq. 8**

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[43] Social networks and voice communications, for instance.

[44] Cloud services (Dinh, Lee, Niyato, & Wang, 2011), video (Radio et al., 2012), gaming (Feijóo, 2012), augmented reality (Wei, Wang, Ramnath, & Ramanathan, 2012)

Being:

V_{user}	Guaranteed user data rate (see Table 5.11)
V_{app}	Data rate of the most resource demanding application (see Table 5.11)
QoS	Quality of service in terms of availability of access to guaranteed resources. Established at 90% for every year of the period
p_{day}	Probability of using the application on a particular day (60%-100%)
l_{usage}	Length of the session using the application, in minutes (5-100)
$t_{session}$	Duration of the time slot more likely to access the application access, in minutes (240-1400)
P_1	Probability of a user accessing the application at a specific time
n	Ratio of the data rate of the most resource demanding application to the guaranteed user data rate, i.e., the maximum number of users that can simultaneously use the most resource demanding application at full speed
P_n	Probability of n users accessing the application at a specific time
P_m	Probability of congestion, i.e., probability of m users using the guaranteed data rate at the specified QoS
$c(m,n)$	Combinatorial number of degree n
m	Maximum number of users at the guaranteed data rate, i.e., contention ratio

Table 5.10 – Main parameters in scenarios for the data rate evolution per subscriber over 2011-2020

Year	*2011*	*2012*	*2013*	*2014*	*2015*	*2016*	*2017*	*2018*	*2019*	*2020*
Worldwide mobile data traffic (Petabytes)	0.60	1.30	2.40	4.20	6.90	10.80	15.45	22.00	29.68	40.00
Growth y-y of total mobile data	-	118%	85%	75%	64%	57%	43%	42%	35%	35%
Usage scenario	Accessing standard TV through tablet, downloading content from cloud computing services, playing online games through tablet and smartphone				Accessing HDTV through tablet, downloading content from cloud computing services, playing advanced online games through tablet and smartphone, using simple augmented reality applications				Ultra HDTV, cloud computing, advanced online games, augmented reality apps	
Maximum Vapp (Mbps)	0.26	0.58	1.11	1.94	3.00	4.44	6.28	8.59	11.09	17.36
Vuser (Mbps)	1	1	2	2	3	5	5	5	5	5
Contention ratio	91	16	16	3	2	2	1	1	1	1
Base station throughput (Gbps)	1.8	1.8	1.8	1.8	1.8	1.8	3.6	3.6	3.6	3.6

5.3.3.DEMAND CALCULATION

The third part of the baseline evolution addresses the forecasting of the ultra-broadband demand. Forecasting processes are widely used to assess the diffusion of innovations in telecommunications (Fildes & Kumar, 2002; Meade & Islam, 2006), and in particular in the mobile domain (see for instance Hamoudia and Scaglione (2012) for mobile social networking).

For NGANs, a simple and robust forecasting tool is needed because the deployments of these technologies are currently in a very incipient stage and susceptible to associated techno-economic uncertainties. This is an issue confronted already by main experts in the field of demand forecasting of technology markets.

In this research for the evolution of user adoption, models based on s-shaped growth were used. The data set used to perform the penetration calculations has been obtained from the Spanish National Regulatory Agency (CMT, Telecommunications Market Commission). S-curve models have proven to provide the most robust fit in estimating the adoption of telecom technologies in the long term (Cardenas, Garcia-Molina, Sales, & Capmany, 2004) when compared to other models such as time series. These innovation diffusion models define an s-shaped curve for the new adopters' cumulative function, which asymptotically approaches a saturation threshold that is typically exogenously determined.

In the first stage of the research the simple logistic curve (Eq. 9) used by Cauwels and Sornette (2011) was selected due to its easy interpretation.

$$x_{logisitic}(t) = \frac{M}{1+e^{-(\alpha(t-t_0))}} \qquad \textbf{Eq. 9}$$

In this equation, M defines the market saturation level, t_0 denotes the intermediate point at which 50% of the M value is achieved determining the start of the deceleration of the diffusion process, and α corresponds to a parameter for defining the growth rate of the curve. The final market saturation levels have already been set for both fixed and mobile technologies in 2020 in section 4.3. T_0 and α are obtained by fitting the data into each market.

In the research, the demand forecasting exercise consists of a two-stage procedure (Figure 5.11). In the case of fixed networks, the forecast uses first, the evolution of the market saturation level starting from the current penetration of fixed broadband lines, and then, the share of FTTH or FTTx/VDSL technologies in the broadband market. The combination of both estimations results in the evolution of each technology number of lines until 2020. Mobile penetration assessment follows a similar pattern. In the first stage, the evolution of the total number of mobile subscribers is estimated, and in the second stage, the number of smartphones (see Table 5.15) with broadband capabilities is estimated with regard to the total number of subscribers, as future 4G subscriptions are expected to be directly related to these devices

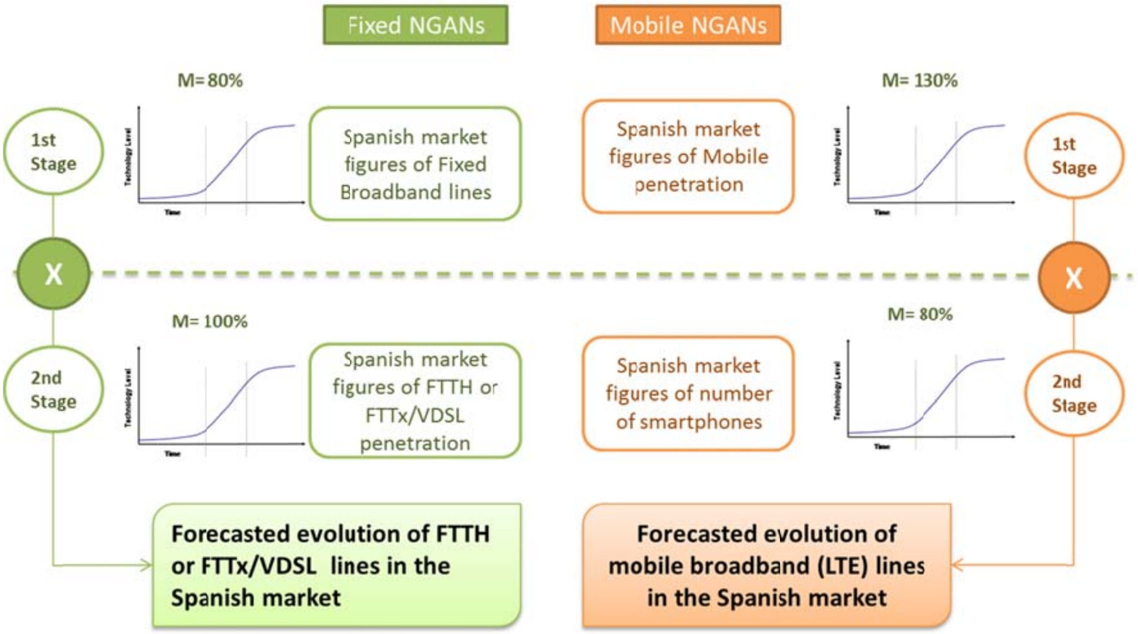

Figure 5.11 – Demand forecasting process for fixed and mobile ultra-broadband technologies

The results of the forecast are summarized in Table 5.11 (and detailed for each year in Table 5.12).

Table 5.11 – Results of the forecast for the evolution of fixed and mobile technologies in Spain for 2020.

Technology	Year	2011	2020
FTTH	Fixed BB penetration (lines per premises)	68.27%	79.08%
	FTTH penetration (over total Fixed BB)	1.47%	98.12%
	FTTH penetration (per 100 inhabitants)	0.24%	30.34%
	Number of FTTH lines (millions)	0.11	14.18
FTTx/VDSL	Fixed BB penetration (lines per premises)	68.27%	79.08%
	VDSL penetration (over total Fixed BB)	0.80%	99.80%
	VDSL penetration (per 100 inhabitants)	0.19%	30.31%
	Number of VDSL lines (millions)	0.09	14.16
LTE	Mobile penetration (subscribers per 100 inhabitants)	123.58%	128.47%
	LTE penetration (over total mobile penetration)	28.58%	79.80%
	LTE penetration (per 100 inhabitants)	49.28%	102.51%
	Number of mobile BB lines (millions)	16.85	47.74

With the aim of assessing the accuracy of the forecasting model and the impact of using different s-curve models for the demand calculation process, an additional exercise regarding the mobile domain was performed using two other innovation diffusion models. The first was the Gompertz model (Eq. 10) used by Tahon et al. (2011) and Cardenas et al. (2004), and the other was the Bass model (Eq. 11) used by J.I. López, Orero, and Arroyo (2007). These two models together with the logistic one are the most robust and accurate approaches available for long-term forecasting under uncertain conditions, according to the Friedman test (Meade & Islam, 1995).

$$x_{Gompertz}(t) = Me^{-be^{-iat}} \qquad \textbf{Eq. 10}$$

In this equation b sets the displacement and a determines the growth rate or scaling of the function.

$$x_{Bass}(t) = pM + (1 + q - p)x(t-1) - \frac{q}{M}x(t-1)^2 \qquad \textbf{Eq. 11}$$

In the Bass model, p denotes the coefficient of innovation, q denotes the coefficient of imitation, and $x(t\text{-}1)$ is the number of users at time $t\text{-}1$.

For the calculations, the diffusion model functions selected are linearized in one or two steps, depending on the growth model. To obtain the different parameters of the Logistic and Gompertz functions, the ordinary least squares (OLS) method is applied (Cauwels & Sornette, 2011), and a nonlinear parametric sweep is used for the Bass model (Samples, Byom, & Daida, 2007). Table 5.13 summarises the results for each model.

Table 5.12 – Penetration of broadband lines for the Spanish scenario.

	Year	***Fixed broadband data***								***Mobile broadband data***		
		Fixed broadband lines	***Penetration over the total number of premises***	***Number of FTTH subscribers***	***Penetration rate over the total number of premises***	***Market share over total fixed BB lines***	***Number of VDSL subscribers***	***Penetration rate over the total number of premises***	***Market share over total fixed BB lines***	***Penetration over the total population (%)***	***Number of devices (millions)***	***Penetration of Smartphone devices over the total population (%)***
Actual Spanish market values	***2009***	9799486	51.3%	10192	0.06%	0.10%	8636	0.05%	0.09%	108.36%	7.81	15.64%
	2010	10649632	55.4%	35586	0.20%	0.33%	29904	0.17%	0.28%	111.45%	9.91	19.55%
	2011	11164966	59.7%	110168	0.61%	0.99%	89802	0.50%	0.80%	118.76%	17.85	34.69%
	2012	12254117	61.8%	462457	2.58%	3.77%	343278	1.91%	2.80%	121.06%	24.84	49.13%
Forecasted values	***2013***	12791003	64.3%	1561602	8.70%	12.21%	1135607	6.33%	8.88%	122.78%	30.07	63.20%
	2014	13203947	67.8%	4360613	24.29%	33.03%	3271544	18.23%	24.78%	124.19%	35.83	75.62%
	2015	13515408	70.6%	8597913	47.90%	63.62%	7120654	39.67%	52.69%	125.33%	40.30	85.37%
	2016	13746876	72.9%	11837494	65.95%	86.11%	10861534	60.51%	79.01%	126.26%	43.41	92.29%
	2017	13917012	74.6%	13311474	74.16%	95.65%	12903095	71.88%	92.71%	127.01%	45.42	96.85%
	2018	14041058	76.0%	13863205	77.23%	98.73%	13722101	76.44%	97.73%	127.61%	46.64	99.72%
	2019	14130965	78.7%	14080022	78.44%	99.64%	14034469	78.18%	99.32%	128.09%	47.35	101.47%
	2020	14195850	79.08%	14181379	79.00%	99.90%	14167036	78.92%	99.80%	128.47%	47.74	102.51%

Table 5.13 – Estimated parameters in forecasting models

Year	*Parameter*	*Step 1* *Calculation of mobile lines*	*Step 2* *Smartphone penetration calculation*
Logistic model	α	0.057069	0.523862
	t_0 (Year/quarter)	1988/III	2012/II
Gompertz model	a	0.052	0.291672
	b	0.368395	2.745845
Bass model	p	0.0241	0.022
	q	0.03	0.39

Table 5.14 shows the quarterly data from 2005 to 2011. As the objective of the calculation is a long-term forecast, seasonal adjustments are used to smooth fluctuations. Therefore, a new data set is obtained using a moving average of order five. The last four quarters of the data are set apart for calculating the measurement error, as described below, and are not used in the estimation process. As used previously, and according to the predictions in the literature (see for instance Jefferies (2011)), the market saturation for mobile penetration in Spain will be 130% mobile subscriptions per 100 inhabitants.

For the second stage, yearly market data on the number of smartphones and tablets in Spain has been obtained from several industry sources (see Table 5.15). Major industry sources predict that the market saturation, that is, the total number of mobile devices that can access the broadband mobile network, will be 80% of the total market in 2020 (Jefferies, 2011).

Table 5.14 – Current data on the penetration of mobile lines in the Spain case study; source: CMT

Quarter/Year	*Penetration for total population (%)*	*Seasonally adjusted penetration data (%)*
I/2005	90.4	
II/2005	92.3	
III/2005	94.4	94.3
IV/2005	96.25	96.2
I/2006	98.1	98.3
II/2006	99.9	100.2
III/2006	102.7	101.6
IV/2006	104	102.6
I/2007	103.5	103.7
II/2007	103.1	104.5
III/2007	105.1	105.2
IV/2007	106.9	106.1
I/2008	107.3	107.5
II/2008	108.2	108.6
III/2008	109.8	109.5
IV/2008	110.8	110.5
I/2009	111.5	111.6
II/2009	112.4	112.7
III/2009	113.7	113.4
IV/2009	115.1	114.1
I/2010	114.4	115.1
II/2010	115.1	116.0
III/2010	117	116.7
IV/2010	118.2	117.7
I/2011	118.9	118.8
II/2011	119.4	119.8
III/2011	120.3	
IV/2011	122.1	

Table 5.15 – Annual number of smartphones for 2009-2012; source: industry data compiled by authors

Year	*Number of devices (millions)*	*Penetration of smartphone devices relative to the total number of mobile lines (%)*	*Penetration variation*
2009	7.809	15%	-
2010	9.907	19%	+4%
2011	17.855	33%	+14%
2012	24.840	44%	+11%

Additionally, the accuracy of the forecast derived from using each model is evaluated by studying the forecasting errors and their fitting capacity. No particular method is recommended to compare the diffusion models because the fitting capacity is “largely unrelated” to forecasting performance (Hardie, Fader, & Wisniewski, 1998). Two measures are combined with the basic principles of model evaluation (J.S. Armstrong, 2001) to choose the most suitable model, as described below. The mean absolute error (MAE) and the median relative absolute error (MdRAE) are used to measure the forecasting error (see Eq. 12 and Eq. 13), as recommended in the literature (J. Scott Armstrong & Collopy, 1992; Willmott & Matsuura, 2005). While there are other common measures of error, such as the root mean square error (RMSE), the measures selected here are more suitable for assessing the average model performance (Willmott & Matsuura, 2005). The model fits are evaluated by the modified R-squared coefficient (Eq. 17). Models with different number of parameters can be compared using the Akaike information criterion (AIC) (J.I. López et al., 2007) (Eq. 18); however, this criterion is not use as a comparison criterion in this research because all the examined models use two parameters. In practice, the AIC is mainly used to uncover overfitting from using an excessive number of parameters in the estimation. Nevertheless, the AIC is included with the fitting capacity measures for completeness In the calculations for smartphone and tablet penetration (in the second stage of the forecasting process), only the fitting capacity is determined because the scarcity of data does not allow data to be set aside to assess the forecasting error.

y_i	Estimated value
$\bar{y}$	Average of the estimated values
$f(x_i)$	Real value
$\overline{f(x_\iota)}$	Average of the real values
n	Number of values used for the estimation
k	Number of parameters estimated in each function

Mean absolute error (MAE)

$$MAE = \frac{1}{n}\sum_{i=1}^{n}|y_i - f(x_i)| \qquad \textbf{Eq. 12}$$

Median relative absolute error (MdRAE) **Eq. 13**

1st step: Calculate the relative absolute errors (RAE) of the time series values

$$RAE = \frac{|y_i - f(x_i)|}{\left|y_i - \overline{f(x_\iota)}\right|}$$

2nd step: Sort the list in order of the error values obtained

3rd step: a) If n is odd: MdRAE= median value of the list

b) If n is even: MdRAE=average value of the central values of the list

Fitting capacity measures

Residual sum of squares (SSR)

$$SSR = \sum_{i=1}^{n} \left(y_i - f(x_i)\right)^2 \qquad \text{Eq. 14}$$

Total sum of squares (SST)

$$SST = \sum_{i=1}^{n} f(x_i)^2 - n\overline{f(x_i)}^2 \qquad \text{Eq. 15}$$

Regression sum of squares (SSReg)

$$SSReg = SST - SSR \qquad \text{Eq. 16}$$

Coefficient of determination (R-squared)

$$R - squared = R^2 = \frac{SSReg}{SST} = 1 - \frac{SSR}{SST} \qquad \text{Eq. 17}$$

Akaike information criterion (AIC)

$$AIC = n \times Ln\left(\frac{SSR}{n}\right) + 2k \qquad \text{Eq. 18}$$

After the completion of both forecasting processes, the total mobile is found by directly combining the smartphone market share and the total number of forecasted mobile lines, as shown in Figure 5.12. The two stages of the forecast are rather different. A mature market is considered in the first stage, and therefore rather confident predictions are obtained. However, the devices market is still emerging, although it is developing quickly, and data are scarce for this market. Thus, the estimates obtained in this second step are not very reliable, as shown by the error measurements and the criteria (see Table 5.16 for the detailed estimation results).

Table 5.16 – Penetration forecasting results

Model	*Year*	*Penetration of mobile lines relative to the total population (%)*	*Number of mobile lines (millions)*	*Smartphone technology penetration relative to all mobile lines (%)*	*Penetration of 4G technology relative to the total population (%)*	*Total number of 4G lines forecasted*
Logistic	***2011***	118.76	55.51	31.32	37.26	17.42
	2012	121.06	56.59	42.83	51.85	24.24
	2013	122.78	57.39	53.89	66.16	30.92
	2014	124.19	58.05	62.96	78.19	36.558
	2015	125.33	58.58	69.50	87.10	40.72
	2016	126.26	59.02	73.77	93.15	43.54
	2017	127.01	59.36	76.40	97.03	45.35
	2018	127.61	59.65	77.95	99.47	46.49
	2019	128.09	59.87	78.84	100.99	47.20
	2020	128.47	60.05	79.35	101.94	47.65
Gompertz	***2011***	117.58	54.96	32.28	37.95	17.74
	2012	119.82	56.01	42.39	50.79	23.74
	2013	121.67	56.87	51.29	62.40	29.17
	2014	123.19	57.58	58.61	72.21	33.75
	2015	124.44	58.17	64.35	80.08	37.43
	2016	125.47	58.65	68.70	86.19	40.29
	2017	126.31	59.04	71.91	90.83	42.45
	2018	126.99	59.36	74.25	94.29	44.07
	2019	127.55	59.62	75.93	96.85	45.27
	2020	128.01	59.83	77.13	98.73	46.15
Bass	***2011***	118.76	55.51	24.92	29.50	13.78
	2012	121.32	56.71	40.12	48.67	22.75
	2013	123.03	57.51	52.51	64.58	30.18
	2014	124.42	58.16	60.16	74.80	34.96
	2015	125.53	58.68	66.41	83.31	38.94
	2016	126.43	59.09	71.11	89.84	41.99
	2017	127.14	59.43	74.39	94.52	44.18
	2018	127.64	59.66	76.55	97.70	45.67
	2019	128.11	59.88	77.91	99.81	46.65
	2020	128.48	60.05	78.75	101.18	47.29

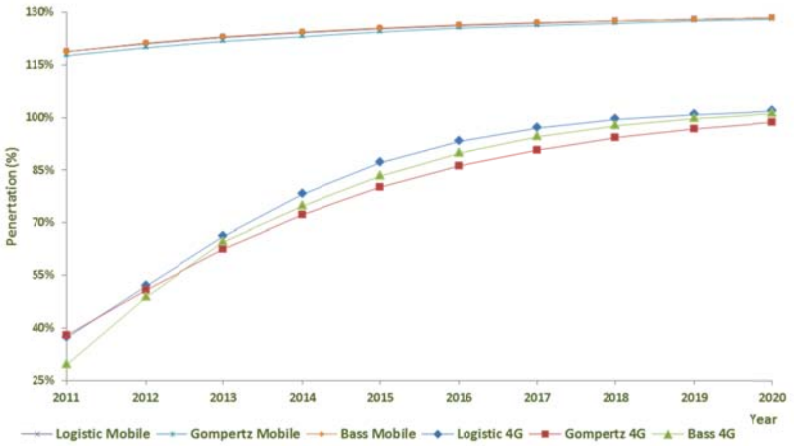

Figure 5.12 – Results of the 4G demand forecast (% of total number of mobile subscribers)

The measured errors and the fitting capacity in Table 5.17 and Table 5.18 show that the Bass model is the most reliable model. While the R-squared measure of this model is lower in the second stage of the process compared to the first stage, this difference is not very significant, and all of the measures are the best for this model in the first stage. In any case it can be anticipated that the sensitivity analysis performed will show the low impact of using one model or other in the overall results. Therefore, the baseline is based on the forecast using the Logistic model, which was the first choice because of the simplicity and the widespread use in similar models.

Table 5.17 – Forecasting error for the mobile lines penetration calculations

Error	*Logistic model*	*Gompertz model*	*Bass model*
MAE	0.0297	0.0178	0.0032
MdRAE	4.2774	2.5424	0.4594

Table 5.18 – Fitting capacity measures

Forecasting step	*Model*	*SSR*	*SST*	*SSReg*	*R-squared*	*AIC*
Calculation of mobile lines	***Logistic***	0.0096	0.1238	0.1142	92.2%	-181.73
	Gompertz	0.0009	0.1238	0.1229	99.3%	-239.20
	Bass	0.0002	0.1035	0.1033	99.8%	-262.97
Smartphone penetration calculation	***Logistic***	0.0013	0.0535	0.0522	97.6%	-26.09
	Gompertz	0.0023	0.0535	0.0513	95.7%	-23.86
	Bass	0.0068	0.0386	0.0317	82.2%	-19.48

5.3.4.DEPLOYMENT STRATEGY

The values obtained using the demand forecasting processes determine the target of potential subscribers for the operators' network deployments each year across the demographic scenario. Operators may follow considerably different strategies for rolling out the network in each zone to achieve this overall target by using different combinations of the number of users in the different zones. There can be different conditions for the selection of the deployment strategy:

- Operators own benefit strategies: maximization of profits, achieving critical mass of users, or anticipating regulatory conditions and/or conflicts.
- Legal impositions or license general conditions: the obligations resulting from the acquisition of the operating license, other governmental recommendations related with regional equity or environmental issues, or ICT / Information Society development plans.
- General economic conditions or financial market requisites.

The evolution of the network along the deployment stage, according to the selected strategy, governs its long term energy consumption behaviour. Even during the deployment, yearly energy consumption depends on networks parameters such as: target coverage, rate of deployment (determined by the penetration forecasting), density zones selected for deployment, and level of take-up.

Therefore, it seems important to understand the impact of the deployment strategies selected in the rolling-out phase of the network in the energy consumed along the years of the deployment. A scenario methodology has been applied with the aim of highlighting and defining the diverse network deployment strategies of both operators and regulators along the deployment that will determine the consumption during and also once completed this stage during the steady-state operation process. The deployment stage time framework is as already mentioned 10 years, a typical figure for the telecom industry.

The first step in the deployment strategy consists of defining a coverage target across density zones for the complete deployment stage. Next step refers to the annual rate to achieve this target coverage. This rate is expressed as a percentage of the total network coverage target per year. Both combined translate into a deployment chart defining the deployment coverage share of a specific density zone at a given year. The figure in each table cell specifies the state of the coverage of the total subscribers of the density zone.

The strategies for network development can be placed on a two-dimensional graph as a function of two sets of parameters. First the x-axis shows the zone prioritization that takes place in the deployment phase (Figure 5.13). Due to diverse factors (i.e. achieving first high population municipalities, reaching rural areas,…) the network deployment stage prioritizes the rolling-out in specific zones. This implies that the roll-out is not in all cases carried out to meet a homogeneous target in every zone. For example an operator could prefer to deploy the mobile access network first in rural areas because in the urban ones a competing fibre-based access network is already deployed. This visualization of the strategy only throws a general perspective of the different profiles of coverage for all density zones.

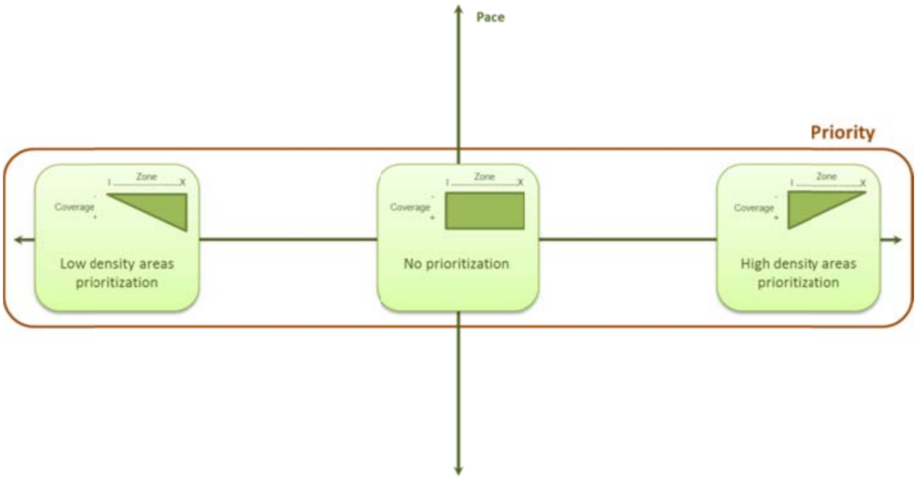

Figure 5.13 – Graphical explanation of the deployment priority axis

The other parameter is the deployment pace (Figure 5.14), this is the annual growth of the network. The strategy could include the need of totally covering zones or reaching intermediate coverage targets at a given year, so the roll-out is not in all cases carried out at a constant rate. For example an operator could be obliged to accelerate the deployment due to competition or regulation. This gives an overall overview of the pace and not specific assumptions for each zone.

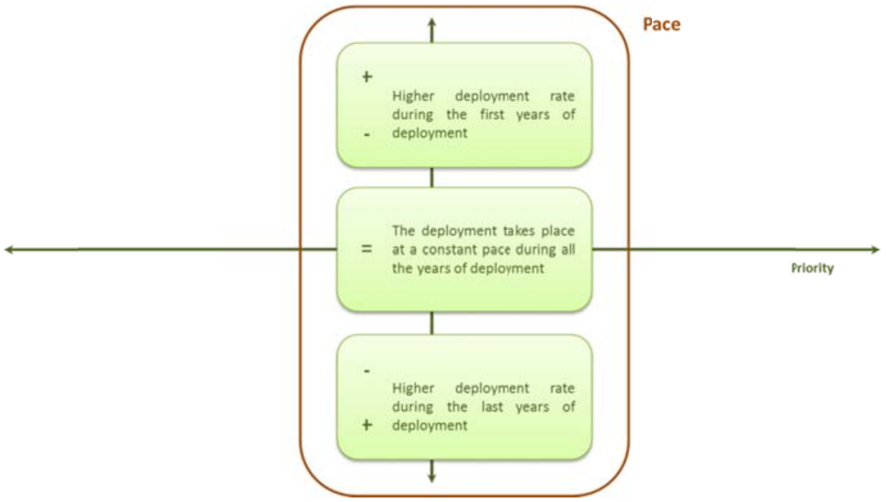

Figure 5.14 – Graphical explanation of the deployment pace axis

The scenarios selected for the analysis are a combination of the parameters described (see Figure 5.15). These were thought before performing the demand calculation assuming a complete demographic scenario roll-out.

The neutral scenario takes no zone prioritization, and a constant year-to-year pace of 10% of the total number of subscribers per zone (1/10 of the total at each of the ten years). These assumptions derive in a constant 10% growth of the total energy consumption level at each year until the last year where the maximum level of energy consumption in the complete scenario is achieved.

The scenario A focus is placed on the network deployment in low density areas. This can result as a consequence of conditions in the license. For instance mobile networks have been subject to this type of conditions in Spain and Germany. The pace for the first year is set at half the coverage target, and this proportion is kept up to the last year of deployment. In the last year of deployment pace is equal to the remaining coverage required to meet the coverage target.

In scenario B the focus is on the network deployment of high density areas. This scenario can arise when no regulations are imposed on operators and they aim for the most profitable zones. The pace is the same as in scenario A.

In scenario C the focus is again on the deployment of low density areas. However there is a disagreement between regulatory conditions and operators preferences that is gradually resolved. Therefore the pace for the last year is set at half the coverage target, and this proportion is kept up to the first year of deployment. In the first year of deployment pace is equal to the remaining coverage required to meet the coverage target.

Finally in scenario D the focus is on the deployment in high density areas. However the situation of economic crisis delays the deployment, thus the target pace is the same as the one set for scenario C.

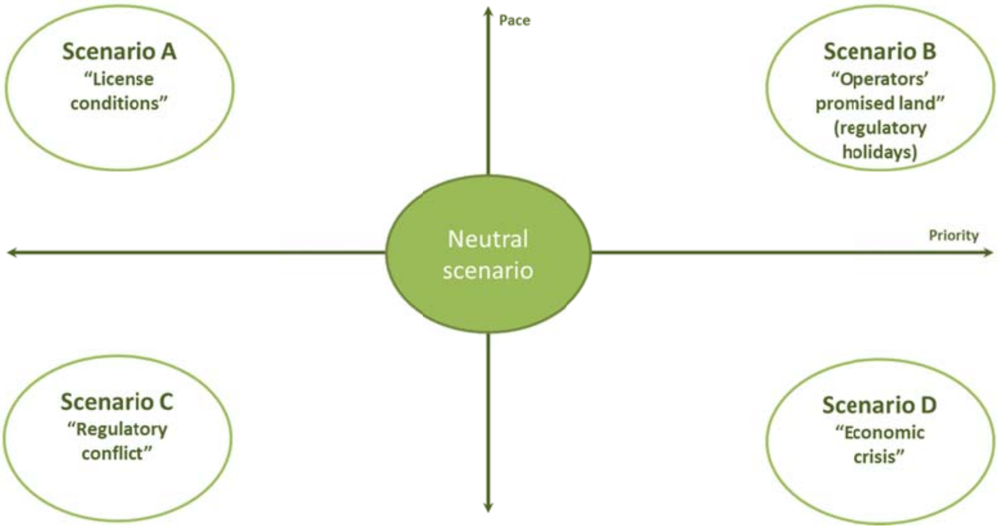

Figure 5.15 – Different scenarios for the deployment strategy analysis

Once the complete network design is performed according to actual penetration values in each of the population density zones is calculated, operators may follow considerably different strategies for rolling out the network in each zone. Therefore, the deployment process establishes the order in which the zones are deployed and the coverage target levels for each zone

The commercially simplest option was chosen for the baseline: the deployment starts in the highest-density zone and moves into subsequent zones until the coverage objective is achieved. The simple rationale behind this approach consists of decreasing the costs of deployment per potential subscriber as much as possible, as in this industry, profitability is based on the average return per user. Note that this strategy is not always chosen, primarily because of different regulatory conditions, so an alternative scenario was also designed in order to determine the impact of modifying the deployment strategy can have in the final energy consumption. These deployment strategies along with their target levels of coverage are detailed in Table 5.19.

Table 5.19 – User allocation strategies determined for the different zones and population of each of them according to the Spanish demographic scenario

	Density zone	***I***	***II***	***III***	***IV***	***V***	***VI***	***VII***	***VIII***	***IX***	***X***	***Total***
	Population in the zone according to demographic data (inhabitants)	2707360	6300119	3832203	8596709	5016333	11326891	3574008	4406394	668735	317055	***46745807***
Coverage strategy selected for the model (Strategy H)		*Following this strategy, operators would first deploy networks in higher density zones and when the each density zone reaches its maximum target coverage next one is started to be covered*										
	Deployment and filling sequence	1	2	3	4	5	6	7	8	9	10	
Fixed Networks	Target coverage (% of premises)	100%	100%	90%	80%	76%	70%	50%	50%	40%	40%	76.10%
	2012 No. of inhabitants per zone	171323	-	-	-	-	-	-	-	-	-	171.323
	2020 No. of inhabitants per zone	1083918	2351705	963318	2092656	1265506	2791370	1127939	1544809	291097	142851	13655168
Mobile Networks	Target coverage (% of population)	125%	125%	110%	110%	95%	95%	85%	80%	65%	65%	101.96%
	2012 No. of inhabitants per zone	3384200	7560143	4215423	9456380	200051	-	-	-	-	-	24816233
	2020 No. of inhabitants per zone	3384200	7875149	4215423	9456380	4765516	10760546	3037907	3525115	434678	174882	47629797
Strategy variation (Strategy L)		*This strategy variation proposes to first deploy the network in lower density zones, according to the filling order stated in the next cells.*										
	Deployment and filling sequence	10	9	8	7	6	5	4	3	1	2	
Fixed Networks	Target coverage (% of premises)	90%	90%	65%	65%	70%	70%	85%	85%	90%	90%	76.12%
	2012 No. of inhabitants per zone	-	-	-	-	-	-	-	-	171.323	-	171323
	2020 No. of inhabitants per zone	1075430	2351705	963318	2092656	1265506	2791370	1127939	1544809	291097	151340	13655168
Mobile Networks	Target coverage (% of population)	110%	110%	100%	95%	100%	100%	105%	105%	105%	100%	101.93%
	2012 No. of inhabitants per zone	-	-	-	2355958	4765516	10760546	3037907	3304796	40.241	190233	24816233
	2020 No. of inhabitants per zone	3352997	7875149	4215423	9456380	4765516	10760546	3037907	3525115	434678	206086	47629797

Therefore the different distributions of subscribers, resulting from the combination of the forecasting process and the deployment strategy, across the ten density zones, and along the 10-year period are shown in the next tables.

Table 5.20 – Demand allocation for FTTH (PtP and GPON)

Demand	I	II	III	IV	V	VI	VII	VIII	IX	X
2011	110168	-	-	-	-	-	-	-	-	-
2012	462457	-	-	-	-	-	-	-	-	-
2013	1204353	357249	-	-	-	-	-	-	-	-
2014	1204353	2613005	543255	-	-	-	-	-	-	-
2015	1204353	2613005	1422747	3090691	267117	-	-	-	-	-
2016	1204353	2613005	1422747	3090691	1554765	1951933	-	-	-	-
2017	1204353	2613005	1422747	3090691	1554765	3389521	36392	-	-	-
2018	1204353	2613005	1422747	3090691	1554765	3389521	588123	-	-	-
2019	1204353	2613005	1422747	3090691	1554765	3389521	804940	-	-	-
2020	1204353	2613005	1422747	3090691	1554765	3389521	906297	-	-	-

Table 5.21 – Demand allocation for FTTx/VDSL

Demand	I	II	III	IV	V	VI	VII	VIII	IX	X
2011	89802	-	-	-	-	-	-	-	-	-
2012	343278	-	-	-	-	-	-	-	-	-
2013	1135607	-	-	-	-	-	-	-	-	-
2014	1204353	2067191	-	-	-	-	-	-	-	-
2015	1204353	2613005	1422747	1880550	-	-	-	-	-	-
2016	1204353	2613005	1422747	3090691	1554765	975973	-	-	-	-
2017	1204353	2613005	1422747	3090691	1554765	3017534	-	-	-	-
2018	1204353	2613005	1422747	3090691	1554765	3389521	447019	-	-	-
2019	1204353	2613005	1422747	3090691	1554765	3389521	759387	-	-	-
2020	1204353	2613005	1422747	3090691	1554765	3389521	891954	-	-	-

Table 5.22 – Demand allocation for LTE

Demand	I	II	III	IV	V	VI	VII	VIII	IX	X
2011	3384200	8190155	4790254	484580	-	-	-	-	-	-
2012	3384200	8190155	4790254	7177065	-	-	-	-	-	-
2013	3384200	8190155	4790254	10316051	3389100	-	-	-	-	-
2014	3384200	8190155	4790254	10316051	5768783	3382371	-	-	-	-
2015	3384200	8190155	4790254	10316051	5768783	7850345	-	-	-	-
2016	3384200	8190155	4790254	10316051	5768783	13025925	-	-	-	-
2017	3384200	8190155	4790254	10316051	5768783	13025925	-	-	-	-
2018	3384200	8190155	4790254	10316051	5768783	13025925	1163717	-	-	-
2019	3384200	8190155	4790254	10316051	5768783	13025925	1872446	-	-	-
2020	3384200	8190155	4790254	10316051	5768783	13025925	2268877	-	-	-

6. COST ANALYSIS

This section establishes a simplified model for making approximate cost calculations on the deployment and use of NGAN, based on a ten year period and on the same assumptions (architectures, design, demographic scenario,…) used for energy calculations.

6.1. DEPLOYMENT COSTS

The calculation process is designed “from the bottom up” and consists basically of determining the size of the basic coverage unit for each technology (local exchange access area for fixed networks and cell for mobile networks) and the number of them in the different zones that compose the demographic scenario.

All the data considered for costs projections have been compiled from industry players at 2010 prices, either publically or through direct interviews. Data on lengths, types of terrain and re-use of ducts are based on own estimations.

6.1.1. FIXED NETWORKS

The wired access network for FTTx technologies is broken down into six separate sections, as shown in Figure 6.1. There are up to eight A segments per exchange and one B and C segments per cabinet. There is also only one D and E segments per distribution point and one F segment per premise. In multi-dwelling units (blocks of flats), there are not E and F segments as the distribution point is at the entrance of the building. The in-building wiring costs replace them.

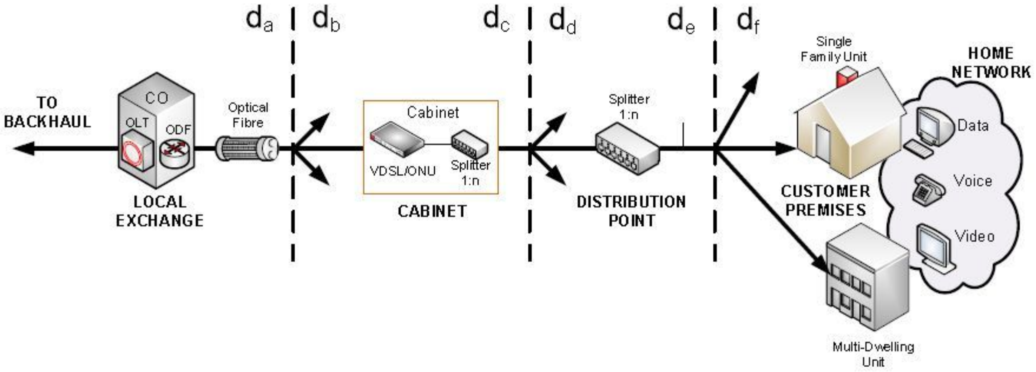

Figure 6.1 – Architecture for fixed networks deployment cost calculation

For the calculation of the deployment costs sizing figures are shown in Table 6.1 (similar to the ones in Table 4.3 or energy calculations). Nor division points nor cabinets would be strictly required for zones IX-X as the lines could be directly connected to the exchange in a point to point configuration. However, it has been preferred to replicate a more flexible FTTx architecture due to the high degree of dispersion of the premises in these zones.

Note that the tree topology is not the only possible architecture for a NGAN. It would be possible to also use a ring-based topology where the cabinets are directly connected among them. According to Analysis Mason (2008) in some areas the total distance of the duct required under a ring topology may be 30% less that for an equivalent tree topology. However, as the tree topology has a relatively high rate of duct re-use, it has been considered that it entails lower overall costs for FTTx technologies. In addition maintaining the network architecture from the energy analysis allows more comparisons based on the same framework.

Table 6.1 – Specific network design features for fixed cost calculations

Zone	I	II	III	IV	V	VI	VII	VIII	IX	X
Number of users per access area (n_{area})	16,384	16,384	16,384	16,384	16,384	16,384	4,096	2,048	512	256
Minimum number of fibres at the exchange (n_{fibre})	256	256	256	256	256	256	64	32	8	8
Total splitter ratio ($r_{split} = r_{split1} \times r_{split2}$)	8x8	8x8	8x8	8x8	8x8	8x8	8x8	8x8	1x8	1x4
Number of fibres at each A segment (n_{fibreA})	96 (min 64)	96 (min 64)	96 (min 64)	96 (min 64)	96 (min 64)	96 (min 64)	24 (min 16)	16 (min 8)	16 (min 2)	16 (min 2)
Number of division points at A-B (n_{divAB})	4	4	4	4	4	4	4	4	4	4
Number of fibres at each B segment (n_{fibreB})	16 (min 8)	16 (min 8)	16 (min 8)	16 (min 8)	16 (min 8)	16 (min 8)	8 (min 4)	8 (min 2)	3 (min 2)	3 (min 2)
Number of cabinets (n_{cab})	32	32	32	32	32	32	16	16	4	4
Number of fibres at each C segment (n_{fibreC})	96 (min 64)	96 (min 64)	96 (min 64)	96 (min 64)	96 (min 64)	96 (min 64)	48 (min 32)	24 (min 16)	24 (min 16)	16 (min 6)
Number of division points at C-D (n_{divCD})	32	32	32	32	32	32	16	16	4	4
Number of fibres at each D segment (n_{fibreD})	16 (min 6)	16 (min 6)	16 (min 6)	16 (min 6)	16 (min 6)	16 (min 6)	16 (min 6)	16 (min 6)	16 (min 6)	16 (min 6)
Number of distribution boxes (n_{box})	342	342	342	342	342	342	86	43	11	11

Civil works, passive and active equipment costs for wired NGAN technologies are shown in Table 6.2. The costs of the optical elements are supposed the same, irrespective of technology to allow a potential migration from FTTC/B/xDSL technologies to FTTH. The cost assumptions are based upon the hypothesis that the network roll-out will take place over a period, during which the average costs for certain elements will fall (active equipment typically).

Table 6.2 – Civil works, passive and active equipment costs for wired NGAN

	Price (€)	***Yearly evolution***[45]	***Comments***
Civil works			
Duct deployment (road) (c_{duct-r})	70 (per m)	Inflation increase	Average of conventional trenching and microtrenching. For any technology
Duct deployment (footpath) (c_{duct-f})	50 (per m)	Inflation increase	idem
Duct deployment (soft ground) ($c_{duct-sg}$)	30 (per m)	Inflation increase	idem
Aerial deployment ($c_{duct-aer}$)	8 (per m)	Inflation increase	No ducts are required. For any technology
Sub-duct deployment (c_{sduct})	1,5 (per m)	Inflation increase	Relevant for any operator, alternative in particular, when inserting sub-duct in existing ducts. For any technology
Cable installation (c_{cinst})	10 (per m)	Inflation increase	For any type of cable and any type of duct and aerial installations. For any technology
Exchange cabinet (c_{cab-e})	3600	5% fall	Able to accommodate ODF, splitter, ONU and xDSL equipment
Division point (c_{div})	600	5% fall	For separation of fibres/cables at a-b and c-d segments. Includes fibre fusion and boxes as required
Field (street) cabinet (c_{cab})	23000	2% fall	Able to accommodate ODF, MDF, power unit, AC/DC converter, batteries and xDSL equipment.
Distribution point boxes (c_{box})	2500	2% fall	Outdoor cabinet for last mile FTTH GPON splitters. Up to 48 subscribers per boxAverage price.
Distribution point boxes (c_{box})	250	2% fall	Average price. Only 10% require upgrading for FTTC/B/VDSL
In-building wiring (c_{mdw})	200	5% fall	Per premise. Only for FTTH technology and multi-dwelling units.
Passive equipment			
Fibre cable (c_{fibre}) 96 FO	6,5 (per m)	3% fall	
Fibre cable (c_{fibre}) 16 FO	2 (per m)	3% fall	
Fibre cable (c_{fibre}) 8 FO	1,3 (per m)	3% fall	
Copper cable	0	-	Existing copper does not need to be upgraded
Migration of existing copper lines (c_{mig})	20	Inflation increase	Per line. For FTTC/B/xDSL technologies
GPON splitter (c_{split})	120	5% fall	The maximum split ratio is 64 (max number of users per fibre). The split ratio of an individual splitter is 8 (therefore, two stages are required)
Optical Distribution Frame (ODF) at local exchange (c_{ODF})	2800	5% fall	Holding up to 256 fibres (and therefore up to 64x256 max number of customers)
Optical Network Unit (ONU) at cabinet (c_{ONU})	1000	5% fall	Holding 64 fibres (and therefore 64x64 max number of customers). Only used if competition takes place from the cabinet
Active equipment			
Optical Line Termination (OLT) card at local exchange (c_{OLT})	30000	10% fall	Each card holds 640 users (10 ports at 64 users per port)
Aggregation switch at local exchange (c_{switch})	3000	10% fall	10 Gb/s of switching capacity per OLT card (640 users)
Mini-VDSLAM at cabinet or distribution point box (c_{VDSL})	2000	10% fall	Each supports 64 users. For FTTC/B/xDSL technologies
Battery for VDSL at cabinet (c_{batt})	1000	5% fall	For FTTC/B/xDSL technologies

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[45] In real prices, unless otherwise stated

The costs of each type of deployment are adjusted according to the geotype for cable lengths (Table 6.3) and for types of terrain (Table 6.4).

Table 6.5 shows the average fraction of premises in multi-dwelling units (blocks of flats), as well as the average number of premises per multi-dwelling building by geotype.

Table 6.3 – Average distances in wired access as a function of the geotype

Geotypes	d_a*(m)*	d_b*(m)*	d_c*(m)*	d_d*(m)*	d_e*(m)*	d_f*(m)*
Ia (> 10 000 inh/km2)	250	750	150	30	10	5
Ib (> 10 000 inh/km2)	500	1500	300	60	15	10
IIa (10-5 000 ihn/km2)	350	1000	250	50	10	10
IIb (10-5 000 ihn/km2)	500	1500	500	100	15	20
IIIa (5-3 000 inh/km2)	250	1000	300	50	10	10
IIIb (5-3 000 inh/km2)	500	1500	500	100	15	20
IVa (3-1 000 inh/km2)	250	750	300	50	10	10
IVb (3-1 000 inh/km2)	750	2000	500	100	20	20
Va (1000 – 500 inh/km2)	150	500	250	50	10	10
Vb (1000 – 500 inh/km2)	500	1500	750	150	15	30
VIa (500 – 100 inh/km2)	100	250	300	50	10	10
VIb (500 – 100 inh/km2)	500	1500	500	100	20	30
VIIa (100 – 50 inh/km2)	50	200	200	40	10	10
VIIb (100 – 50 inh/km2)	250	1000	1000	200	30	70
VIIIa (50 – 10 inh/km2)	50	150	350	60	10	15
VIIIb (50 – 10 inh/km2)	200	500	1000	200	30	100
IX (10 – 5 inh/km2)	100	300	800	120	20	60
X (<5 inh/km2)	100	300	800	120	20	60

Table 6.4 – Types of terrain in wired access as a function of the geotype

Geotypes	*Fraction d_a d_d road (%)*	*Fraction d_a d_d footpath(%)*	*Fraction d_a d_d soft (%)*	*Fraction d_e – d_f footpath (%)*	*Fraction d_e – d_f soft (%)*	*Fraction d_e – d_f aerial (%)*
Ia (> 10 000 inh/km2)	15	85	0	99	0	1
Ib (> 10 000 inh/km2)	15	85	0	99	0	1
IIa (10-5 000 ihn/km2)	15	85	0	90	5	5
IIb (10-5 000 ihn/km2)	15	85	0	90	5	5
IIIa (5-3 000 inh/km2)	15	85	0	80	10	10
IIIb (5-3 000 inh/km2)	15	85	0	80	10	10
IVa (3-1 000 inh/km2)	10	85	5	55	30	15
IVb (3-1 000 inh/km2)	10	85	5	55	30	15
Va (1000 – 500 inh/km2)	5	75	20	55	25	20
Vb (1000 – 500 inh/km2)	5	75	20	55	25	20
VIa (500 – 100 inh/km2)	5	75	20	55	25	20
VIb (500 – 100 inh/km2)	5	75	20	55	25	20
VIIa (100 – 50 inh/km2)	5	45	50	40	30	30
VIIb (100 – 50 inh/km2)	5	45	50	40	30	30
VIIIa (50 – 10 inh/km2)	5	35	60	35	25	40
VIIIb (50 – 10 inh/km2)	5	35	60	35	25	40
IX (10 – 5 inh/km2)	5	25	70	30	20	50
X (<5 inh/km2)	5	25	70	25	15	60

Table 6.5 – Fraction of premises in multi-dwelling units and average number of premises per building as a function of the geotype

Geotypes	*Fraction of premises in multi-dwelling units (fr_{mdw})*	*Average premises per building*
Ia (> 10 000 inh/km2)	90	8,58
Ib (> 10 000 inh/km2)	80	9,52
IIa (10-5 000 ihn/km2)	80	8,92
IIb (10-5 000 ihn/km2)	70	10,05
IIIa (5-3 000 inh/km2)	70	6,66
IIIb (5-3 000 inh/km2)	60	7,60
IVa (3-1 000 inh/km2)	60	4,56
IVb (3-1 000 inh/km2)	50	5,28
Va (1000 – 500 inh/km2)	50	3,59
Vb (1000 – 500 inh/km2)	40	4,24
VIa (500 – 100 inh/km2)	40	2,32
VIb (500 – 100 inh/km2)	30	2,75
VIIa (100 – 50 inh/km2)	30	1,28
VIIb (100 – 50 inh/km2)	20	1,42
VIIIa (50 – 10 inh/km2)	20	1,08
VIIIb (50 – 10 inh/km2)[46]	10	1,00
IX (10 – 5 inh/km2)	10	1,00
X (<5 inh/km2)	5	1,00

Table 6.6 shows the appropriate fractions of re-use for the different segments of the access network for those cases where existing ducts can be re-used. There are three different origins for re-use of ducts: those from the incumbent operator, those already in use by the cable operators and those from utilities (sewer, water, gas, etc). The impact of the re-use of ducts is assumed to be significantly reduced in the lower density geotypes (rural). The costs for cables and installation are assumed to remain the same independently of new or re-used ducts.

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[46] For the last three geotypes, as the number of buildings is higher that the number of premises (meaning that a relevant number of buildings is empty), it is assumed that each non-empty building is equivalent to one premise.

Table 6.6 – Percentage of duct re-use (fr) as a function of the geotype

Geotypes	$d_a - d_b$ (%)	$d_c - d_d$ (%)	$d_e - d_f$ (%)
Ia (> 10 000 inh/km2)	80	70	50
Ib (> 10 000 inh/km2)	70	60	40
IIa (10-5 000 ihn/km2)	80	70	50
IIb (10-5 000 ihn/km2)	70	60	40
IIIa (5-3 000 inh/km2)	80	70	50
IIIb (5-3 000 inh/km2)	60	40	30
IVa (3-1 000 inh/km2)	80	70	50
IVb (3-1 000 inh/km2)	60	40	30
Va (1000 – 500 inh/km2)	60	40	30
Vb (1000 – 500 inh/km2)	60	40	30
VIa (500 – 100 inh/km2)	60	40	30
VIb (500 – 100 inh/km2)	40	20	10
VIIa (100 – 50 inh/km2)	60	40	30
VIIb (100 – 50 inh/km2)	40	20	10
VIIIa (50 – 10 inh/km2)	40	20	10
VIIIb (50 – 10 inh/km2)	40	20	10
IX (10 – 5 inh/km2)	40	20	10
X (<5 inh/km2)	40	20	10

For FTTH, according to the model depicted for wired access networks, the total deployment cost per access area (CA_{dp}) is given by:

$$\begin{aligned} CA^i_{dp} = {} & c_{ODF} + c_{cab-e} + (c_{OLT} + c_{switch}) Int\left[\frac{n^i_{area}}{640} + 1\right] \\ & + d^i_{total}\left(c_{inst} + c_{fibre} + c_{sduct} fr_{sduct}\right) \\ & + d^i_a c^i_{duct-ad}\left(1 - fr^i_{ab}\right) n^i_{divAB} + c^i_{div} n^i_{divAB} \\ & + d^i_b c^i_{duct-ad}\left(1 - fr^i_{ab}\right) n^i_{cab} + \left(c_{cab} + c_{split}\right) n^i_{cab} \\ & + d^i_c c^i_{duct-ad}\left(1 - fr^i_{cd}\right) n^i_{cab} + c^i_{div} n^i_{divCD} \\ & + d^i_d c^i_{duct-ad}\left(1 - fr^i_{cd}\right) n^i_{box} + \left(c_{box} + c_{split}\right) n^i_{box} \\ & + d^i_e c^i_{duct-ef}\left(1 - fr^i_{ef}\right)\left(1 - fr^i_{mdw}\right) n^i_{box} \\ & + d^i_f c^i_{duct-ef}\left(1 - fr^i_{ef}\right)\left(1 - fr^i_{mdw}\right) n^i_{area} \\ & + c_{mdw} fr^i_{mdw} n^i_{area} \end{aligned}$$

Eq. 19

where costs (c) are defined in Table 6.2, costs of ducts (c_{duct}) are calculated from the information inTable 6.2, Table 6.4 and weighted by the relative percentage of distribution among geotypes (a) and (b) according to data supplied in Table Annex.0.4. Fractions of duct re-use (fr) are given in Table 6.6 and fractions of premises in multi-dwelling units (fr_{mdw}) inTable 6.5. Distances (d) are provided in Table 6.3 and weighted by the relative percentage of distribution among geotypes (a) and (b) according to data supplied in Table Annex.0.4. The total length (d_{total}) refers to total wired line used from local exchange to customer premises and it is given by:

$$\begin{aligned} d^i_{total} = {} & d^i_a n^i_{divAB} + (d^i_b + d^i_c) n^i_{cab} + [d^i_d \\ & + d^i_e\left(1 - fr^i_{mdw}\right)] n^i_{box} + d^i_f\left(1 - fr^i_{mdw}\right)] n^i_{area} \end{aligned}$$

Eq. 20

The present value of the total deployment cost per access area ($NPVCA_{dp}$) requires the choice of the number of years for the network roll-out (ny), in this case ten. Costs are considered to be spread evenly as to reach all the potential users according to penetration forecasting for each year. Therefore costs incurred each year are discounted at the WACC ratio:

$$NPVCA^i_{dp} = CA^i_{dp-year\,1} + \sum_{n=2}^{ny} \frac{CA^i_{dp-year\,n}}{(1 + WACC)^{n-1}}$$

Eq. 21

The present value of the total deployment cost per zone ($NPVCZ_{dp}$) is, therefore:

$$NPVCZ^i_{dp} = NPVCA^i_{dp} \frac{n^i_{user}}{n^i_{area}}$$

Eq. 22

where n_{area} is the number of potential users (households and premises) in each zone. Finally the present value of the total deployment cost per zone and per user ($npvcz_{dp}$) is, obviously:

$$npvcz_{dp}^{i} = \frac{NPVCA_{dp}^{i}}{n_{area}^{i}} \qquad \textbf{Eq. 23}$$

For FTTC/VDSL2 the structure of the calculations is rather similar to the FTTH case with the main difference of not including costs for the copper segment. Thus, the total deployment cost per access area (CA$_{dp}$) is given by:

$$\begin{aligned} CA_{dp}^{i} = c_{ODF} + c_{cab-e} + (c_{OLT} + c_{switch}) Int\left[\frac{n_{area}^{i}}{640} + 1\right] \\ + d_{total}^{i}\left(c_{inst} + c_{fibre} + c_{sduct} fr_{sduct}\right) \\ + d_{a}^{i} c_{duct-ad}^{i}\left(1 - fr_{ab}^{i}\right) n_{divAB}^{i} + c_{div}^{i} n_{divAB}^{i} \\ + d_{b}^{i} c_{duct-ad}^{i}\left(1 - fr_{ab}^{i}\right) n_{cab}^{i} + \left(c_{cab} + c_{split}\right) n_{cab}^{i} \\ + d_{c}^{i} c_{duct-ad}^{i}\left(1 - fr_{cd}^{i}\right) n_{cab}^{i} + c_{div}^{i} n_{divCD}^{i} \\ + d_{d}^{i} c_{duct-ad}^{i}\left(1 - fr_{cd}^{i}\right) n_{box}^{i} \\ + (c_{box} + c_{VDSL} + c_{batt}) n_{box}^{i} + c_{mig} n_{area}^{i} \end{aligned} \qquad \textbf{Eq. 24}$$

where costs, distances and distribution are calculated the same way as in FTTH networks. Nevertheless now the total length (d$_{total}$) refers just to the total fibre length used from local exchange to customer premises and it is given by:

$$d_{total}^{i} = d_{a}^{i} n_{divAB}^{i} + (d_{b}^{i} + d_{c}^{i}) n_{cab}^{i} + d_{d}^{i} n_{box}^{i} \qquad \textbf{Eq. 25}$$

The calculations of the different cost values are the same than in the FTTH case.

6.1.2. MOBILE NETWORKS

The wireless access network is broken down into three separate sections, as shown in Figure 6.2. To allow reasonable comparisons with its wired counterpart, a node (mobile switching centre, MSC), where the traffic coming from base stations is gathered, is included in the access part, although in this case it does not have to be in the same place of a wired local exchange, but it requires the same type of optical and switching equipment.

Following the same logic, there are up to eight A segments per node in the access area and one B and C segments per base station. The A and B segments consist in general of an optic fibre cable, but in the low density areas a microwave link can be sufficient to interconnect the base station with the node at the edge of the transport network.

For the calculation of the deployment costs every assumption on network design made for energy calculation process applies, so the figures in Table 5.1 are used along with the penetration rates forecasted.

Table 6.1 also summarizes the main figures resulting from this distribution of users per access area for this type of wired networks. Note also that this deployment is only valid for premises location, and not necessarily for mobility situations (roads, spaces out of urban developments, etc.).

Costs for wireless NGAN technologies that differ from the wired case are shown in Table 6.7. The spectrum fees require some specific considerations. For the "digital dividend" spectrum the approach at Ofcom (2007) has been followed acknowledging its limitations: "the high level of uncertainty and the complexity of some of the inter-relationships between services mean that this type of modelling can at best provide an order of magnitude assessment of value". In the case of the 2.6 GHz band, the auction at Germany in 2010 has been taken as a benchmark. It is also obvious that none of the figures in the document can be taken directly as an indication of auction or contest proceeds. They are just valid for their use in a simulation exercise as the one here.

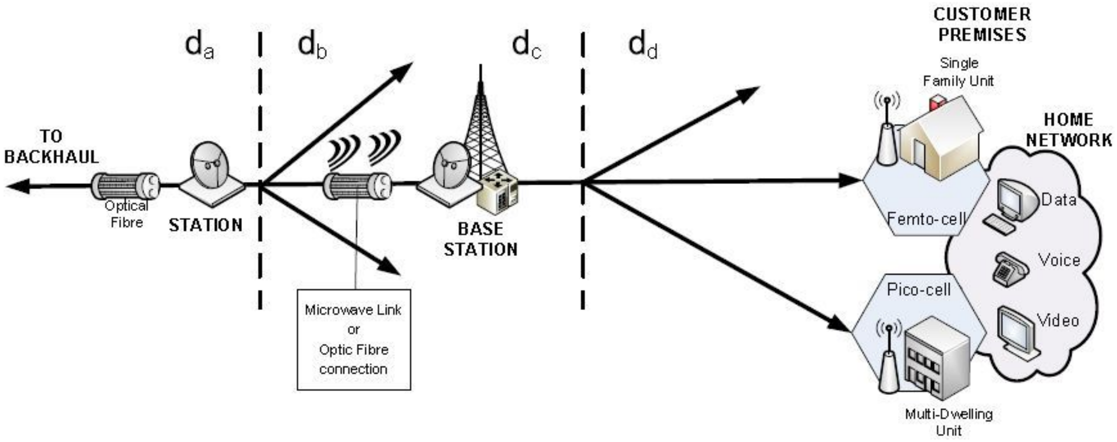

Figure 6.2 – Architecture for mobile networks deployment cost calculation

Table 6.7 – Deployment costs for wireless NGAN

	Price (€)	*Yearly evolution*[47]	*Comments*
Civil works			
Base station deployment ($c_{bs\text{-}d}$)	30.000	5% fall	Per site. For any technology
Spectrum			
Spectrum fees at 800 MHz (c_{spect})	20.000.000	Inflation increase	Per MHz. 20 years license.
Spectrum fees at 2,6 GHz (c_{spect})	2.000.000	Inflation increase	Per MHz. 20 years license.
Administrative licensing	3.500 €		Per site
Active equipment			
Base station at 2,6 GHz (c_{bs})	23.000	10% fall	For LTE. 3 sectors, 20 MHz each
Base station at 800 MHz (c_{bs})	18.000	10% fall	For LTE. 3 sectors, 20 MHz each
Tr-Rx equipment (c_{tr})	4.000	10% fall	For LTE. 2 Tr-Rx per sector
Power supply equipment for base station (c_{pow})	10.000	5% fall	For any technology
Pico-cell (c_{pico})	350	10% fall	Up to 8 users. For any technology
Femtocell (c_{femto})	250	10% fall	For any technology

The cost of each type of deployment is again adjusted according to the geotype as shown in Table 6.3 for cable lengths and Table 6.4 for types of terrain. For mobile networks, moving from the node to the customer premises, the total deployment cost per access area (CA_{dp}) is given by[48]:

$$\begin{aligned} CA_{dp}^{i} = {} & c_{ODF} + c_{cab-e} + (c_{OLT} + c_{switch}) Int\left[\frac{n_{area}^{i}}{640} + 1\right] \\ & + d_{total}^{i}\left(c_{inst} + c_{fibre} + c_{sduct} fr_{sduct}\right) \\ & + d_{a}^{i} c_{duct-ad}^{i}\left(1 - fr_{ab}^{i}\right) n_{divAB}^{i} + c_{div}^{i} n_{divAB}^{i} \\ & + d_{b}^{i} c_{duct-ad}^{i}\left(1 - fr_{ab}^{i}\right) n_{bs}^{i} + (c_{bs-d} + 2c_{bs} \\ & + 12c_{tr} + 2c_{pow}) n_{bs}^{i} + \frac{c_{spect} bw}{n_{area-total}} \end{aligned} \qquad \textbf{Eq. 26}$$

The total length (d_{total}) refers just to the total fibre length used from the equivalent access area to base stations and it is given by:

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[47] In real prices, unless otherwise stated

[48] The same explanation for the parameters used as in fixed networks applies

$$d_{total}^{i} = d_{a}^{i} n_{divAB}^{i} + d_{b}^{i} n_{bs}^{i} \qquad \textbf{Eq. 27}$$

Once calculated the cost per access zone, the process followed to assess the other cost parameters are the same as for fixed networks.

6.2. OPERATING COSTS

For the calculation of the operating costs the number of subscribers at each year resulting from the forecasting process has to be considered.

Table 6.8 presents a summary of the operating costs of a wired NGAN, including their time evolution. For FTTH and for the year n, the yearly total operating costs per access area (CA_{op}) are given by:

$$\begin{aligned} CA_{op}^{i} = n_{area}^{i} \times (c_{drop} + \frac{c_{CPE}}{5} + \frac{c_{batt}}{5} + c_{pow} + c_{nets} + c_{gens} \\ + c_{genm} + c_{bill} + c_{bad} + c_{prov}) \end{aligned} \qquad \textbf{Eq. 28}$$

The calculations for the FTTB/VDSL case are the same just suppressing the cost of the battery and using the appropriate values given in Table 6.8.

The same process as for deployment cost is followed to obtain, the present values of the total operating costs per access area (discounted at the WACC ratio), the present value of the total deployment cost per zone, and the net present value of the total operating costs per zone and per user.

Table 6.8 – Operating costs for wired NGAN. Source: own compilation of industry data

	Price (€)	*Yearly evolution*[49]	*Comments*
Civil works			
Duct rental	2 (per m)	Inflation increase	Only relevant for alternative operators
Passive equipment			
Installation of final drop (c_{drop})	120	Inflation increase	Per user. Incurred only when a customer takes a service. Includes the faceplate at subscriber premises. For any technology
Migration due to churn (c_{churn})	100	Inflation increase	Average value per churned user. It could vary as a function of the access point / unbundling possibilities (at exchange, at cabinet or at distribution box). Includes internal and external migration costs. For any technology
Accomodation of equipment in the exchange	10	Inflation increase	Per user. Only relevant for alternative operators
Active equipment			
Customer Premises Equipment (CPE) (c_{CPE})	100	10% fall	Per user. Including modem, routing and wireless hub. For any technology. Cost per 5 years.
Battery backup (c_{batt})	100	10% fall	Per user. For FTTH as this technology does not include power supply on the wire. Includes maintenance. Cost per 5 years.
Power consumption at exchange (c_{pow})	2	Inflation increase	Per line. Considers the average of a fixed and a variable per KWh charge (30 W consumption per OLT port).
Support and management			
Network support (FTTH) (c_{nets})	6	Inflation increase	Per line
Network support (FTTC/VDSL) (c_{nets})	12	Inflation increase	Per line
General support (FTTH) (c_{gens})	9	Inflation increase	Per line
General support (FTTC/VDSL) (c_{gens})	12	Inflation increase	Per line
General management (c_{genm})	13	Inflation increase	Per line. For any tecnology
Finance and billing (c_{bill})	1	Inflation increase	Per line. For any technology
Bad debts and other costs (c_{bad})	3	Inflation increase	Per line. For any technology
Provision / maintenance (FTTH) (c_{prov})	4	Inflation increase	Per line
Provision / maintenance (FTTC/VDSL) (c_{prov})	12	Inflation increase	Per line

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[49] In real prices, unless otherwise stated

In the case of mobile solutions the approach considered follows the same structure as in wired NGAN, therefore including an additional degree of detail compared to previous stages of the research in which OPEX estimations were based on a percentage of CAPEX. In order to maintain the scheme used with for wired networks, some assumptions about the network and the maintenance costs are made (see Table 6.9). The first part combines the costs assigned to the active parts of the network (fibres, nodes, base stations…), and the network operation costs of the physical network. Those costs can be described as the fixed cost due to the network operation and can be divided into various groups as: civil works, passive equipment maintenance and active equipment maintenance. In addition to the network operation cost, additional costs for marketing, customer service, billing, or administrative sanctions, among others, must be considered (included as general management costs).

$$\begin{aligned} &\mathit{WIRELESS\ NETWORK\ OPEX} \\ &= \mathit{Equipments\ and\ network\ strucutre\ maintenance} \\ &+ \mathit{Other\ Costs\ involved}\ (\mathit{Marketing}, \mathit{Billing}, \dots) \end{aligned} \tag{Eq. 29}$$

As final consideration, it is important to highlight that depreciation periods and amortisation costs have not been considered. Following De-Antonio, Feijóo, Gómez-Barroso, Rojo, and Marín (2006) some typical figures would be the following.

In fixed access networks, the assets are divided into groups with different duration hypothesis:

- passive and active equipment, 10 years;
- cables, 15 years;
- construction elements, 20 years;
- other expenses, 5 years.

In wireless access networks, the assets are also divided into groups:

- network equipment, 8 years (given the speed of technological changes in this area);
- construction elements, 15 years (for the same reason);
- required buildings, 30 years;
- other expenses, 5 years.

Table 6.9 – Summary of operating costs for wireless NGAN. Source: own compilation of industry data

	Comments	*Price (€)*	*Yearly evolution*[50]
Civil works			
Duct rental	Only relevant for alternative operators	2 (per m)	Inflation increase
Site rental	Per site	6.000€	Inflation increase
Passive equipment			
Installation of final drop (c_{drop})	Per user. Incurred only when a customer takes a service. Includes the faceplate at subscriber premises. For any technology	120	Inflation increase
Migration due to churn (c_{churn})	Average value per churned user. It could vary as a function of the access point / unbundling possibilities (at exchange, at cabinet or at distribution box). Includes internal and external migration costs. For any technology	100	Inflation increase
Accommodation of equipment in the exchange	Per user. Only relevant for alternative operators	10	Inflation increase
Active equipment			
Femto and Pico-cells power consumption	Considerations about the power consumption on the cells reception equipment	120	
Femto and Pico-cells equipment technical maintenance	For example: Replacement of equipment due to malfunction	60	
Tx-Rx power consumption		80	Inflation increase
Tx-Rx equipment technical maintenance		30	Inflation increase
Base Station power supply	Per site	1.200	Inflation increase
Base Station equipment technical maintenance	Per site	600	Inflation increase
Sanctions	Per year for the whole network	3.000.000	20% increase
Closures and withdrawals	Per year for the whole network	15.000.000	10% increase
Adaptations	1 of 30 base stations need this type of work a year	1.000	Inflation increase
Support and management			
General management and support (c_{genm})	For any technology	25	Inflation increase
Finance and billing (c_{bill})	For any technology	1	Inflation increase
Bad debts and other costs (c_{bad})	For any technology. Include the debts, churn,	3	Inflation increase

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[50] In real prices, unless otherwise stated

6.3. RESULTS ON THE COST ANALYSIS

Table 6.10 – Current value of capital expenditure (millions of €) for an access area regarding the each density zone and technology

Zone	*FTTH-GPON*	*FTTC-VDSL*	*LTE*
I	4,29	2,98	2,85
II	5,58	3,61	2,84
III	5,79	3,60	2,74
IV	7,03	4,10	2,81
V	9,83	4,49	2,54
VI	10,64	3,91	2,59
VII	3,88	1,29	0,61
VIII	3,42	1,03	0,30
IX	1,35	0,26	0,12
X	0,90	0,26	0,12
Weighted average	**6,86**	**3,29**	**2,24**

Table 6.11 – Current value of capital expenditures (millions of €) for the demand and deployment strategy assumed regarding each density zone and technology

Zone	*FTTH-GPON*	*FTTC-VDSL*	*LTE*
I	345,96	219,17	611,95
II	976,42	576,16	1.421,13
III	551,30	312,28	800,18
IV	1.454,86	773,12	1.766,48
V	1.022,62	426,39	893,07
VI	2.414,07	808,39	2.055,61
VII	940,11	281,93	318,72
VIII	-	-	-
IX	-	-	-
X	-	-	-
Weighted average	**1.330,86**	**582,88**	**1.433,83**
Total	**7.705**	**3.397**	**7.867**

Table 6.12 – Operational expenditure figures for a single year

	FTTH-GPON	*FTTC-VDSL*	*LTE*
Total OPEX (M €)	1.200,34	1.238,08	1.126,47
OPEX per user (€)	210,44	217,06	106,76
General management and support per user (€)	59,77	78,23	32,03

Table 6.13 – Current value of total cost per user (€) regarding each density zone

Zone	*FTTH-GPON*	*FTTC-VDSL*	*LTE*
I	497,70	399,04	250,37
II	584,12	437,56	249,86
III	597,93	436,55	240,54
IV	681,17	467,20	246,58
V	868,18	491,31	222,93
VI	922,66	455,56	227,24
VII	1.247,75	533,14	215,12
VIII	2.041,90	720,47	214,21
IX	3.110,04	734,26	350,86
X	4.074,83	1.238,80	701,71
Weighted average	**975,55**	**498,18**	**240,68**

Table 6.14 – Current value of total costs (millions of €) regarding each density zone

Zone	*FTTH-GPON*	*FTTC-VDSL*	*LTE*
I	2.439,97	2.285,62	1.361,59
II	4.630,78	4.135,26	3.196,77
III	2.277,17	1.994,89	1.764,53
IV	4.827,06	4.118,52	3.430,86
V	2.284,38	1.877,89	1.853,14
VI	4.571,52	3.399,19	3.302,52
VII	898,30	560,48	399,68
VIII	-	-	-
IX	-	-	-
X	-	-	-
Weighted average	**3.203,60**	**2.644,38**	**2.267,56**
Total	**21.929**	**18.372**	**15.309**

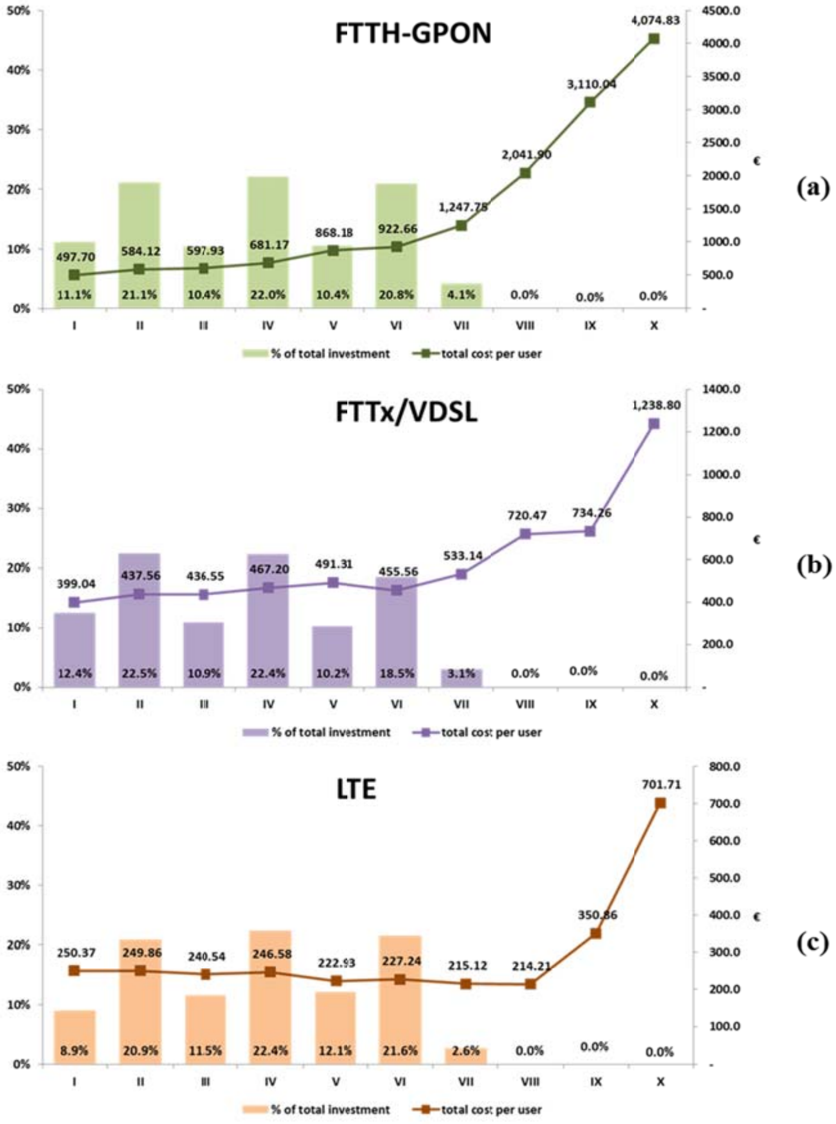


Figure 6.3 – Cost per user for the different density zones and share of the total investment required in each density zone for the forecasted demand scenario

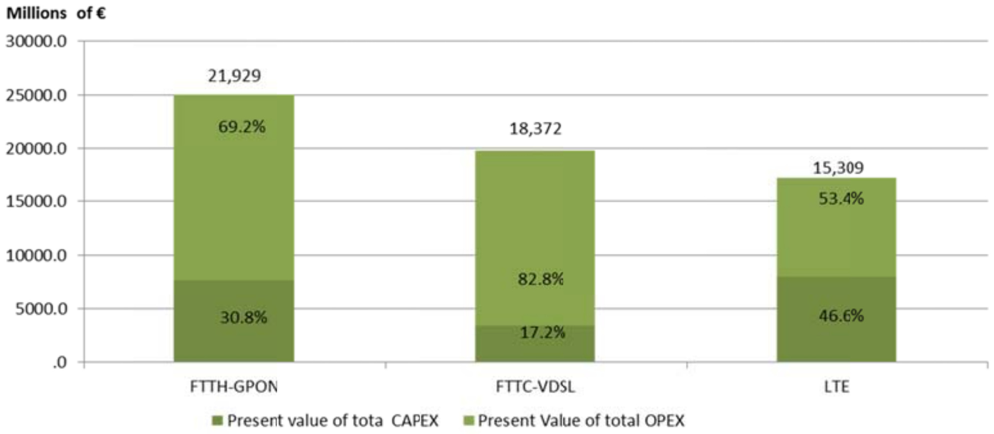


Figure 6.4 – Summary of resulting expenditures for the deployment of access networks

7. USER DEVICES

Aside from the energy consumption due to the usage of the access network, a significant amount of energy is consumed by the user personal digital devices. Although these devices cannot be considered as part of the access network, the usage of the broadband resources provided won't be understood without their inclusion as part of the three major components of the energy consumption in ICTs. In addition while access network consumption affects only the operators' side, this perspective relapses more on the consumers' end.

Mobile handsets, smartphones, tablets, laptops, notebooks … are responsible of the consumption associated with the network. In addition to the expected increase in energy resources, the progressive increment in the amount of devices will translate in the need of more and more resources from the network and subsequently in a necessary resizing of the access network itself.

The objective of this section is therefore to present a basic model that allows assessing the energy consumed by the fleet of devices in the Spanish scenario. Obtaining these figures allows for an interpretation of the impact of the consumption of the devices with regard to the energy consumption due to the network usage.

7.1. ENERGY CONSUMPTION CALCULATION MODEL

Two basic operational modes are defined for user devices: continuous power consumption during usage and an idle state with energy consumption only while recharging the device. Eq. 30 is therefore used for the consumption per device.

$$P_{device}^{day} = (t_{usage} \times p_{usage}) + (t_{recharge} \times p_{recharge} \times n_{recharge}) \qquad \textbf{Eq. 30}$$

This equation takes into considerations diverse factors:

- Time of usage (hours): t_{usage}
- Power required during usage (Wh): p_{usage}
- Time required to recharge (hours) : $t_{recharge}$

- Power required during recharge (Wh): $p_{recharge}$
- Number of recharges required per day: $n_{recharge}$

The model is assumed to be an average for all the days along a year, so the consumption a day can be calculated and then multiplied by 365.

$$P_{device}^{day} = P_{device}^{day} \times 365 \qquad \text{Eq. 31}$$

The specific values used are average values obtained from specifications from manufacturers and vendors of devices and in own estimations based on EC (2011). With the aim of comparing the network and user devices consumptions at the start of the network deployment, and then at the end of it, only values for 2011 and 2020 are presented in Table 7.1 and Table 7.2.

Table 7.1 - Power consumption and usage features of user devices in 2011

User devices consumption features 2011	t_{usage} (hours)	P_{usage} (Wh)	$t_{recharge}$ (hours)	$P_{recharge}$ (Wh)	$n_{recharge}$ (per day)
Laptops	5	60	2	25	0.4
Computers	3	120	-	-	-
Other devices (video games consoles, smart TV,…)	1	150	-	-	-
Smartphones	-	-	1	5	1
Tablets	-	-	5	10	0.25
Router	24	11	-	-	-

With respect to user devices, energy management features will improve their energy profiles (Bojic, Podobnik, & Petric, 2012; CISCO, 2012b; Frenger et al., 2011). The only exception will be routers, as they will manage larger amounts of data, increasing the energy consumed. It has been considered also that the increasing usage of wireless devices will reduce time devoted to other user devices, thus decreasing their total energy consumption (Brandewinder, 2008). The proposed values for the 2020 scenario are:

Table 7.2 - Power consumption and usage features of user devices for 2020

User devices consumption features2020	t_{usage} (hours)	P_{usage} (Wh)	$t_{recharge}$ (hours)	$P_{recharge}$ (Wh)	$n_{recharge}$ (per day)
Laptops	7	45	1	20	0.33
Computers	2	100	-	-	-
Other devices (video games consoles, smart TV,…)	2	125	-	-	-
Smartphones	-	-	1	4	0.5
Tablets	-	-	2.5	8	0.2
Router	24	20	-	-	-

For these comparisons with the consumption of access networks, device consumptions are grouped according to the data traffic nature of the device (see Figure 7.1). Laptops, computers and other devices are considered to belong to fixed networks, while tablets and smartphones are considered to belong to mobile access networks. The off-loading of mobile data traffic via Wi-Fi is considered to assign part of the consumption of mobile devices to fixed networks. Forecasts from the industry are used for off-loading traffic (CISCO, 2012a). Then the energy consumed in the router group is shared between fixed and mobile networks, in proportion to the ratio of fixed and off-loaded mobile traffic to pure mobile data traffic (CISCO, 2012b).

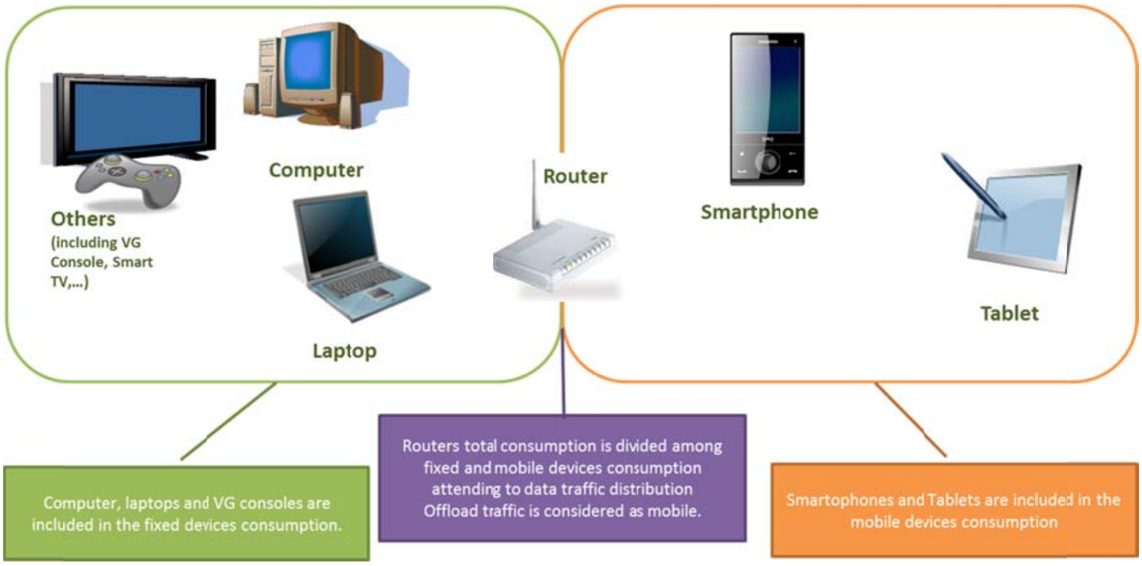


Figure 7.1 – Groups of device energy consumption for comparisons with access network consumption

7.2. SPANISH DEVICE MARKET EVOLUTION

The evolution of user demand is synergic with changes in the user devices market. In fact, according to forecasts (CISCO, 2012b; Jefferies, 2011), the increase in data traffic, especially in the mobile domain, is driven by the increase in the number of wireless devices that provide access to broadband services. Thus, for 2016, there are prospects of the data traffic from wireless devices (61%) exceeding wired device traffic (39%), while in 2011, wired devices accounted for 55% of all traffic.

Currently in Spain, each inhabitant has on average nearly two different devices to access the network, and there are nearly five devices per premise (see Table 7.3 for data obtained from Telefónica (2012)). This places Spain in a relatively high position regarding ICT equipment. Therefore, without the appearance of a new technology/device (as experienced in recent years with the entry of tablets into the market), the number of devices is not expected to dramatically increase. For fixed access devices (computers, laptops and others), the increase in penetration is assumed to be gradually lower due to the migration towards wireless devices and the virtualization of a relevant part of the services delivered by these types of devices (Gartner, 2012). Mobile devices will grow according to the forecast of the S-shaped growth explained in section 5.3.3. The same logic is followed to establish the number of tablets, as the other main source of data traffic for 4G networks, apart from the off-loading to fixed networks. The router devices number relates to the evolution of the penetration of

FTTH technology. Following these assumptions Table 7.4 summarizes the projection of the number of user devices for the year 2020 (see details of device evolution in Table 7.5).

The analysis of the energy consumption of user devices departs from the compilation of the user device market in Spain, as presented in Table 7.3. The distribution of the devices across the demographic scenario was assumed to be proportional to the population and premises distribution.

Table 7.3 – Spanish user device market in year 2011

Device Market in 2012	Number of units (millions)	Penetration of the device among population (%)	Number of devices per premise
Computers	22.71	49%	1.26
Laptops	22.36	48%	1.25
Other devices (video games consoles, smart TV, etc.)	10.05	22%	0.56
Smartphones	17.86	38%	0.99
Tablets	4.77	10%	0.27
Router	10.52	23%	0.59
Total	88.27	189%	4.92

Table 7.4 – Spanish user device market projection for year 2020

Device Market in 2020	Number of units (millions)	Penetration of the device among population (%)	Number of devices per premise
Computers	29.61	63%	1.65
Laptops	29.16	62%	1.62
Other devices (video games consoles, smart TV, etc.)	13.11	28%	0.73
Smartphones	60.67	130%	3.38
Tablets	10.91	23%	0.61
Router	35.75	76%	1.99
Total	179.20	383%	9.98

Table 7.5 – Evolution of the number of user devices according to forecasting assumption for the 2011-2020 period

Device evolution (millions of units)	2011	2012	2013	2014	2015	2016	2017	2018	2019	2020
Computers	22.71	23.84	24.91	25.91	26.82	27.62	28.31	28.88	29.31	29.61
Laptop	22.36	23.48	24.54	25.52	26.41	27.21	27.89	28.44	28.87	29.16
Other devices (video games consoles, smart TV, etc.)	10.05	10.56	11.03	11.47	11.87	12.23	12.54	12.79	12.98	13.11
Smartphones	17.86	26.53	35.03	42.54	48.63	53.13	56.25	58.35	59.74	60.67
Tablet	4.77	7.09	9.36	11.36	12.99	14.19	15.03	15.59	15.96	16.21
Router	10.52	15.63	20.64	25.06	28.65	31.30	33.14	34.38	35.20	35.75
Total	88.27	107.13	125.52	141.87	155.38	165.68	173.15	178.42	182.06	184.50

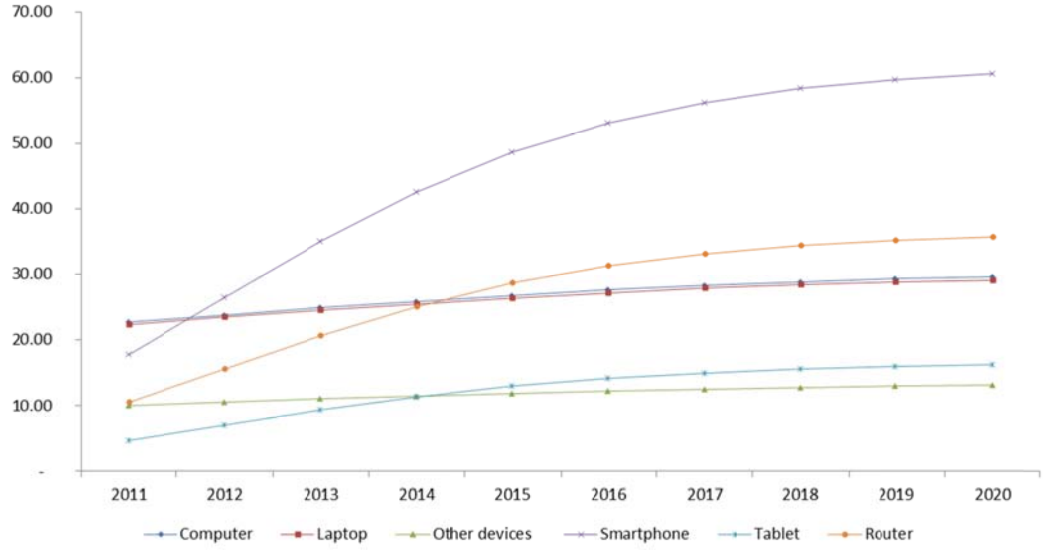


Figure 7.2 – Evolution of the number of user devices in the Spanish market

8. RESULTS AND DISCUSSION

This section introduces a series of results obtained from the application of the energy consumption models at different levels.

First, a general perspective is obtained on the levels of energy consumed by each of the selected technologies along the network deployment period. Some comparisons between the different technologies are then applied in order to draw conclusions about the optimal technology in energy terms. A comparison of the energy consumed by access networks in comparison with that derived from user devices is also included, as well as the results derived from the exercise performed with different diffusion models, as previously explained in Section 5.3.3. As part of the network-related operating costs, an analysis of the specific impact of the cost of energy consumption on these expenses is then included. Finally, a sensitivity analysis is performed regarding different possible variations in the assumptions made in terms of deviations in different parameters from the baseline proposed or in other approaches taken.

The results section ends with a simple note on the repercussions of the energy consumed for the global energy scenario according to the model presented and specific Spanish energy data.

8.1. ACCESS NETWORK ENERGY CONSUMPTION

First, the different energy consumption profiles of the technology choices are analysed. As these profiles evolve along the deployment period, the first and the final year of the timeframe selected are shown regarding the access network unit or, in the case of mobile technology, also regarding the cell unit. To draw a geographical outlook of the energy consumption evolution, the profile of a specific density zone is included; the one selected is density zone VI, as it is the most populated zone of the demographic scenario, with almost 25% of the total population and 10% of the total surface.

Then the particular energy consumption profile of the different access networks' technology choices is shown and commented on. Finally, a summary of the main energy and cost results is shown along with the profile of the costs related to energy consumption according to the energy prices assumed.

8.1.1.FTTH-PTP

The decreasing evolution of the access area consumption (see Figure 8.1) is mainly due to the energy efficiency improvement of active devices in the network. The energy per access area decreases by 38% for every zone.

In PtP technology, customers without service do not need to be connected to an optical port, so the number of premises connected is equal to the number of premises subscribed. For this reason, the consumption per user is constant for every zone, as the energy consumption of the density zone is directly related to the number of users.

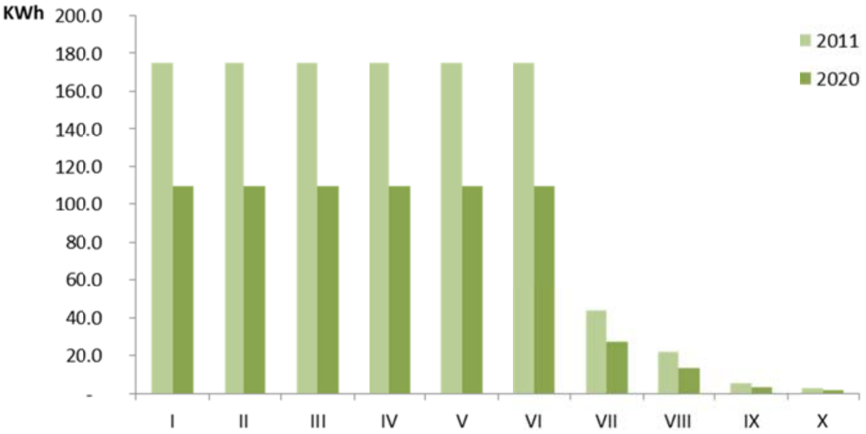


Figure 8.1 – PtP profile of energy consumption per access area for the year 2011

In Figure 8.2 this variation in time is shown particularly for density zone VI. As mentioned, the decrease in the energy consumed per access area coincides with the reduction in the levels of consumption of each active device required in the network.

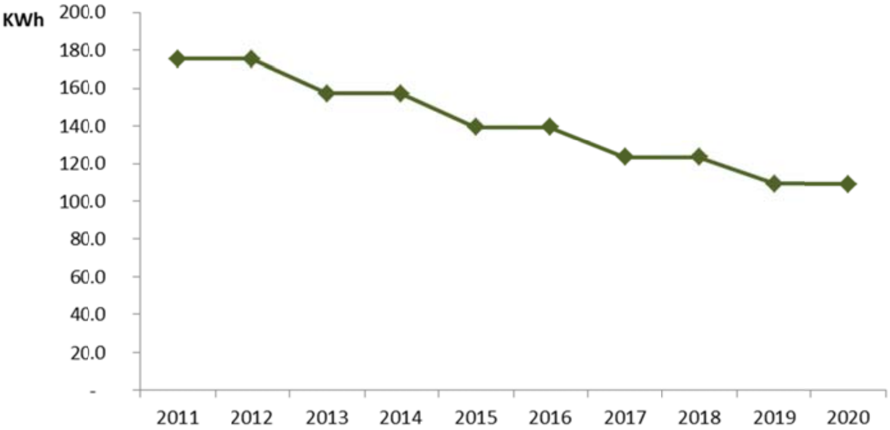


Figure 8.2 – PtP variation profile of energy consumption of a single access area in density zone VI for the period 2011–2020

Even though the energy per subscriber is constant for every zone each year, the decrease in the energy consumption per access area is affected along the deployment period in this same amount of 38%, as shown in Figure 8.3.

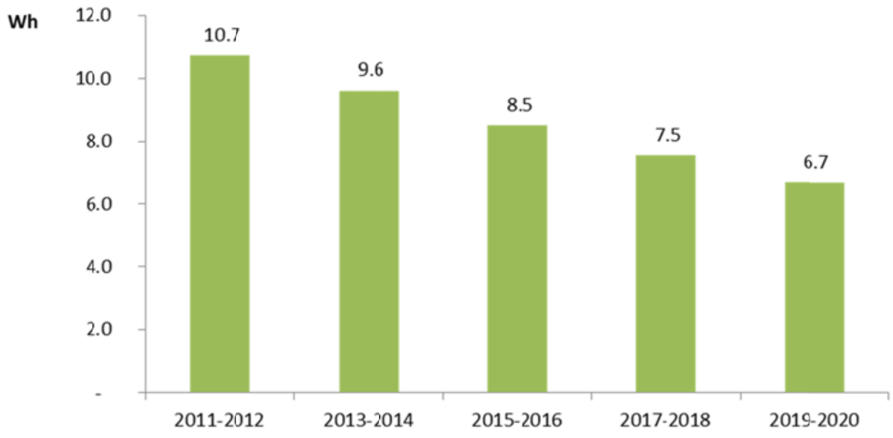


Figure 8.3 – Hourly PtP energy consumption per subscriber in each access zone

In FTTP-PtP access networks, the share of the active element power consumption (Figure 8.4) is constant throughout the ten years of deployment. This characteristic is due to the previously explained fact that the network consumption is defined by the premises subscribed and not by the homes passed. Therefore there is a linear dependency of the energy on the number of users. The percentage of the power consumed by the CPE is 33% and that consumed by the OLT is 67%. The higher contribution of the OLT towards the power consumption share is due to the need to use one interface for each customer, in contrast to other fibre-sharing technology choices where the optical signal is shared by several customers.

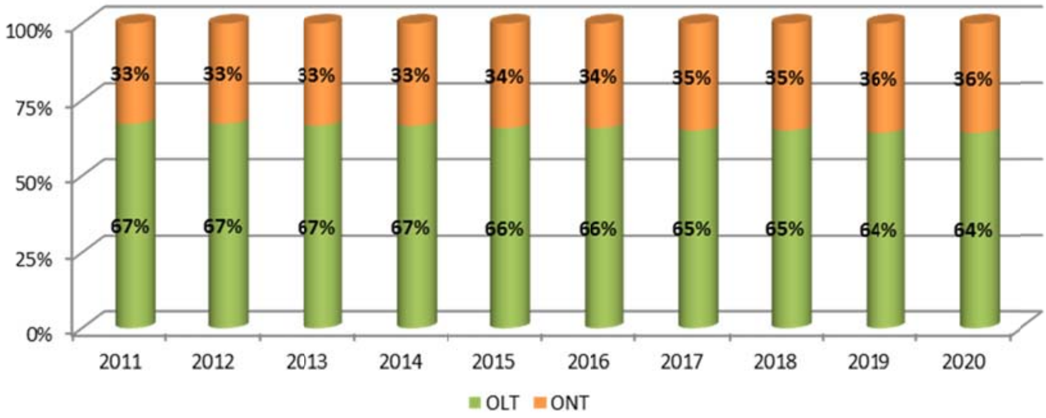


Figure 8.4 – Average energy consumption breakdown for PtP active devices (%)

Once all the density zones have been aggregated and the level of annual energy consumption has been assessed, the evolution profile of this level is shown in Figure 8.5. The growing trend in the first years is due to the high increase in penetration level according to the forecasted values. Even with the improvements in the energy consumption features of the active devices, the increase is significant until the year 2017, when the low increment in the demand level is overtaken by the enhancement of the energy efficiency occurring in this year. Precisely on this date, a complete replacement of first and second year active devices is done along with the ones placed to cover the annual demand requirements. This translates into a reduction in energy consumption of 0.4% with respect to the level in 2016. Once again in 2019 this effect is repeated, reducing the energy consumption level by 10% with respect to the one in 2018. In this case the impact is more significant because the replacement affects a greater amount of devices which were placed in 2013–2014, and the increase in demand is just 2% instead of the 12% that took place in 2017. Regarding the start and end of the period, the energy consumed is 80 times higher in the year 2020. In fact this is not the year with the highest level of consumption, which is 2018, when 0.914 million MW are consumed.

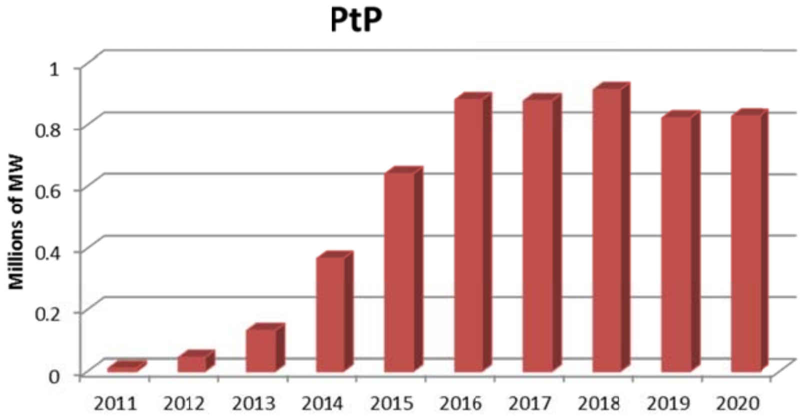
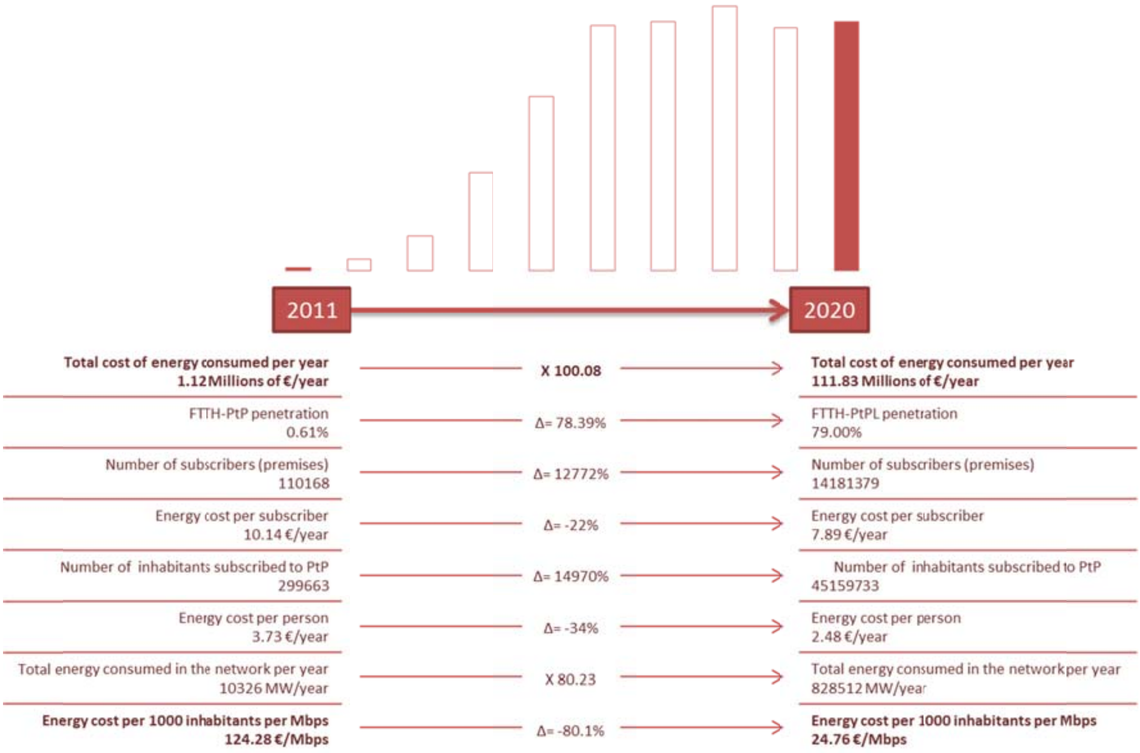


Figure 8.5 – FTTH-PtP annual energy consumption profile

Finally, Figure 8.6 summarizes the figures regarding demand, consumption levels, and costs for the first and the final year of the deployment period. As will be shown in the results for the other fibre-based technology choices, the evolution in the data rate per user provided translates into a large decrease in the energy cost per 1000 habitants per megabit per second. This is in spite of the large increase in the number of subscribers (penetration evolution), due to the evolution of the data rate value, from 30 Mbps at the start of the deployment to 100 Mbps at the end, required to cope with the increase in data traffic over the years.



2011		2020
Total cost of energy consumed per year 1.12 Millions of €/year	**X 100.08**	**Total cost of energy consumed per year 111.83 Millions of €/year**
FTTH-PtP penetration 0.61%	Δ= 78.39%	FTTH-PtPL penetration 79.00%
Number of subscribers (premises) 110168	Δ= 12772%	Number of subscribers (premises) 14181379
Energy cost per subscriber 10.14 €/year	Δ= -22%	Energy cost per subscriber 7.89 €/year
Number of inhabitants subscribed to PtP 299663	Δ= 14970%	Number of inhabitants subscribed to PtP 45159733
Energy cost per person 3.73 €/year	Δ= -34%	Energy cost per person 2.48 €/year
Total energy consumed in the network per year 10326 MW/year	X 80.23	Total energy consumed in the networkper year 828512 MW/year
Energy cost per 1000 inhabitants per Mbps 124.28 €/Mbps	Δ= -80.1%	**Energy cost per 1000 inhabitants per Mbps 24.76 €/Mbps**

Figure 8.6 – Summary of FTTH-PtP consumption and cost calculations

8.1.2.FTTH-GPON

In the GPON case, the reduction of the energy consumed in the starting year of the deployment and the last one is similar to that in the PtP case, but the level varies according to the density zone, due to the specific efficiency in the use of the active devices shared among customers depending on the network sizing parameters.

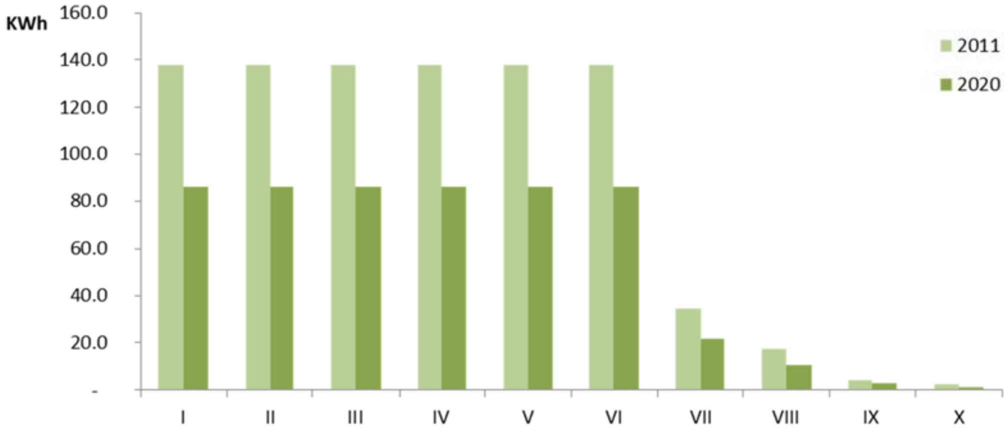


Figure 8.7 – GPON profile of energy consumption per access area for the year 2011

In fact in the analysis of density zone VI, the particularities of the network evolution are shown. In those years when active devices energy profiles are the same, the variation (normally a decrease) is not significant, consequence of the increase in the level of consumption share the uplinks at central office, whose energy profile improve every year. In year 2016, due to the modification of the data rate per user from 30 to 50 Mbps, the energy level increases but by a modest proportion. This effect is also repeated in the year 2020, both times due to the consumption at the local exchanges as a consequence of the variation in the distribution of resources and the modification of the number of uplinks and downlinks required.

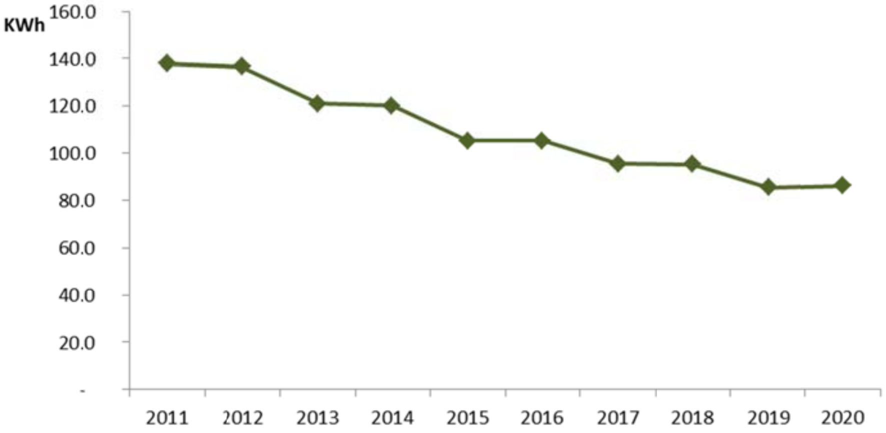


Figure 8.8 – GPON variation profile of energy consumption of a single access area in density zone VI for the period 2011–2020

In terms of energy per subscriber, this decrease is also shown from the start year to the end of the period. Regarding each density zone, from I to IX the level is constant, but the specific sizing of the network in zone X translates in an increment of the energy per subscriber. This is a consequence of the use of local exchanges with the same downlink capacity and only half the uplinks (to cope with the access area subscriber capacity). Nevertheless the increase in the level of consumption is only 6%.

The total decrease is 37%. Sixty-three percent of this improvement is made in the first half of the period and only 37% in the second half.

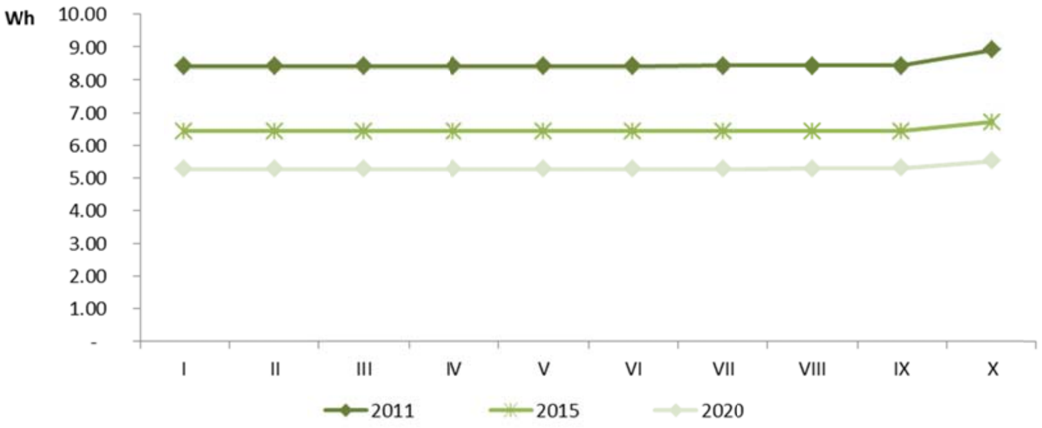


Figure 8.9 – GPON energy consumption per subscriber in each access zone

In FTTH-PON (as will also be shown in FTTx/VDSL and LTE networks), the non-linear dependency of the energy on the number of users connected to the local exchange translates into a variation of the power share of the active elements among the years. These variations are not significant in GPON access networks, as shown in Figure 8.10. But contrary to what happens in PtP networks, the primary contribution to the energy consumption is made by the ONT, due to the higher output required by the laser diodes in FTTHPON and FTTx/VDSL (due to the splitting factor explained previously in Section 2.5.1).

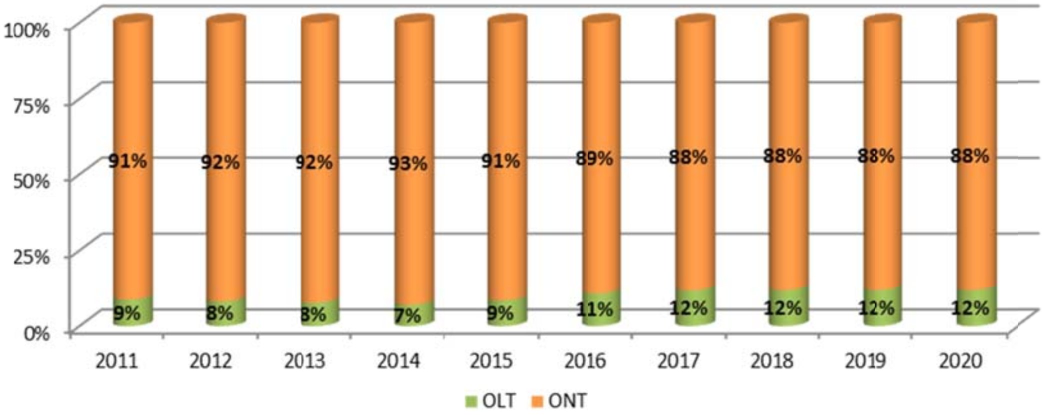


Figure 8.10 – Average energy consumption breakdown for GPON active devices (%)

Regarding the annual level of energy consumed during the GPON deployment, the evolution is presented in Figure 8.11. From the starting year, this evolution is consistent with its limited market penetration, growing according to the s-shaped deployment curve until a mature stage is reached at an energy consumption of approximately 0.75 million MW. Variations in the data rate per user occur in the same years as in the PtP case, but this time do not induce remarkable variations in the energy consumed.

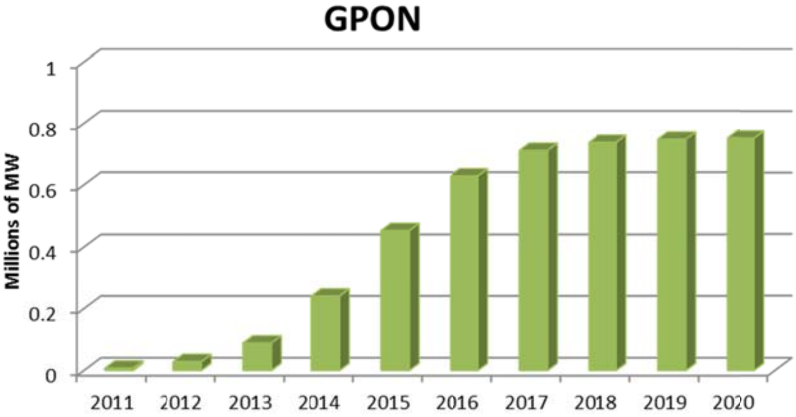
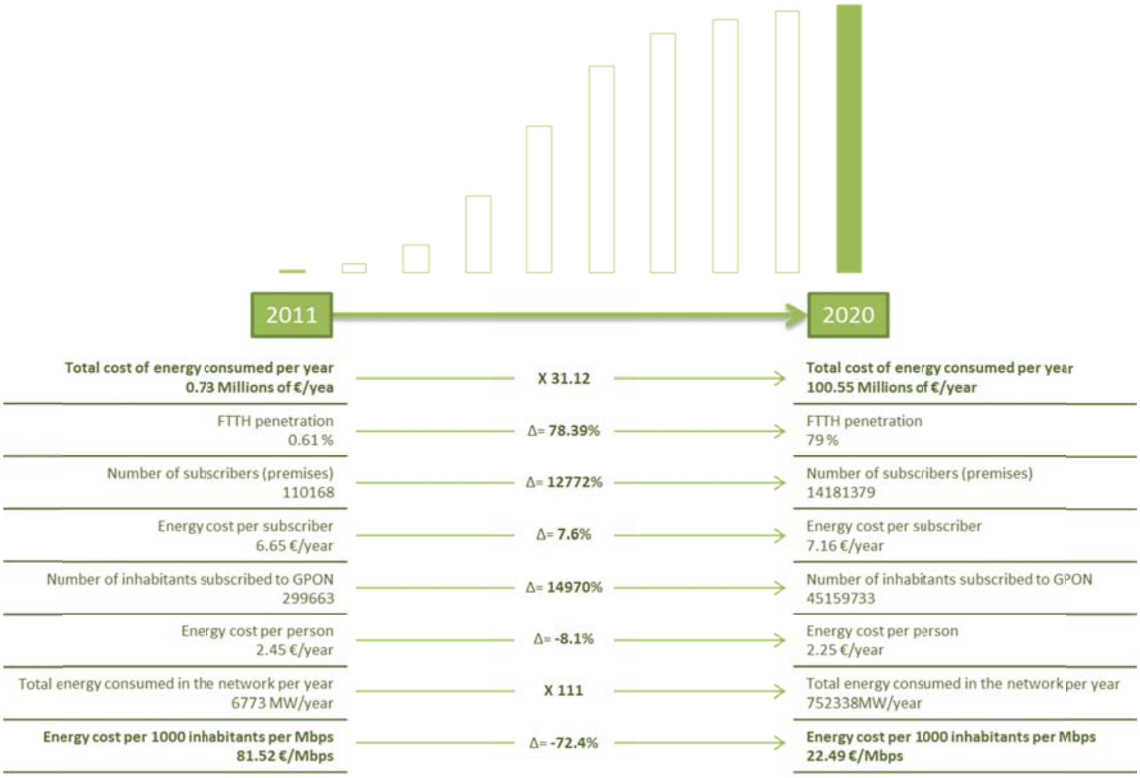


Figure 8.11 – FTTH-GPON annual energy consumption profile

Similarly to PtP technology, the most interesting result is the significant increase in energy consumption within the network and its associated cost along the baseline. This is to be expected, as in both cases the technology has barely commenced the rollout phase (the demand variation is assumed to be the same for both technologies). If the costs per premise (subscriber) or per person are considered, it is also noteworthy that they decrease for FTTH-GPON despite the increase in energy prices. The reason is that in fixed networks energy consumption by user devices depends on the number of subscribers served by the network and evolves with this number.



2011		2020
Total cost of energy consumed per year **0.73 Millions of €/yea**	**X 31.12**	**Total cost of energy consumed per year** **100.55 Millions of €/year**
FTTH penetration 0.61 %	**Δ= 78.39%**	FTTH penetration 79 %
Number of subscribers (premises) 110168	**Δ= 12772%**	Number of subscribers (premises) 14181379
Energy cost per subscriber 6.65 €/year	**Δ= 7.6%**	Energy cost per subscriber 7.16 €/year
Number of inhabitants subscribed to GPON 299663	**Δ= 14970%**	Number of inhabitants subscribed to GPON 45159733
Energy cost per person 2.45 €/year	**Δ= -8.1%**	Energy cost per person 2.25 €/year
Total energy consumed in the network per year 6773 MW/year	**X 111**	Total energy consumed in the networkper year 752338MW/year
Energy cost per 1000 inhabitants per Mbps **81.52 €/Mbps**	**Δ= -72.4%**	**Energy cost per 1000 inhabitants per Mbps** **22.49 €/Mbps**

Figure 8.12 – Summary of FTTH-GPON consumption and cost calculations

8.1.3.FTTx/VDSL

FTTx/VDSL technology shows a much better improvement in its energy consumption per access area from the start to the end of the period. In fact this value reaches a 68% decrease, mainly due to the energy efficiency improvements in cabinets and the equipment on customer premises.

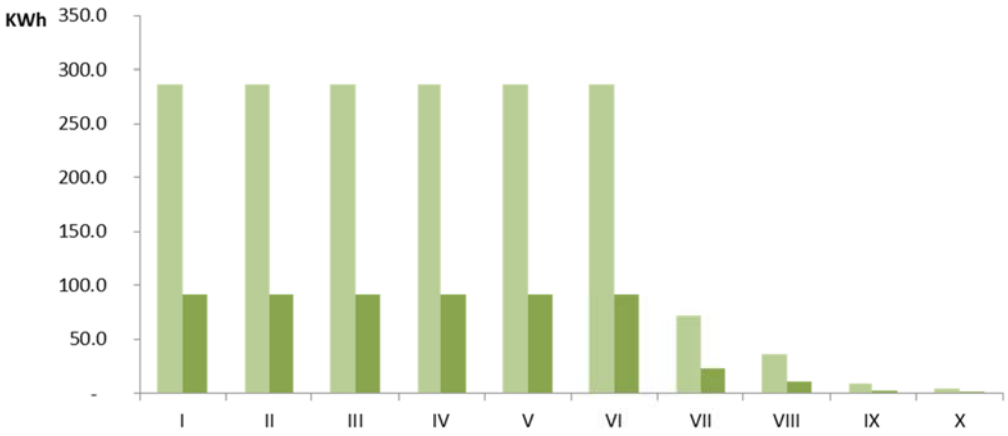


Figure 8.13 – FTTx/VDSL profile of energy consumption per access area for the year 2011

This variation is shown better in Figure 8.14, in which the same effects as in PtP in the years 2016 and 2020 are again present.

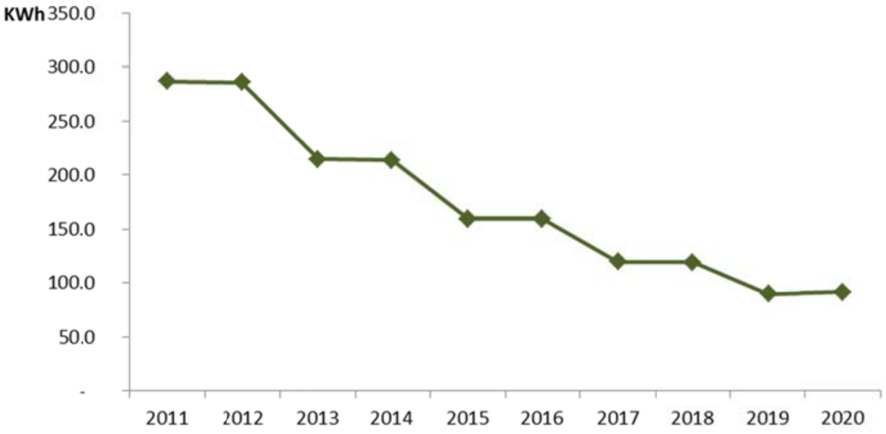


Figure 8.14 – FTTx/VDSL variation profile of energy consumption of a single access area in density zone VI for the period 2011–2020

The total decrease in energy per subscriber for the deployment period goes up to 68%. In the year 2015, a decrease of 44% is already achieved, while the remaining 24% occurs during the following five-year period.

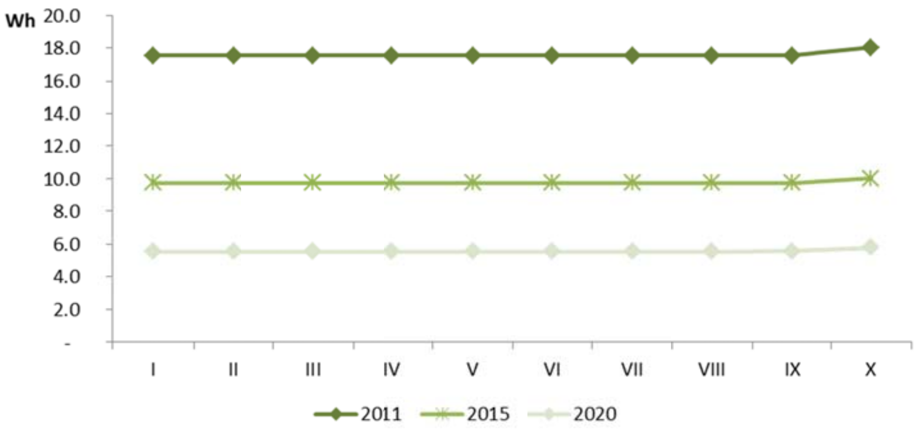


Figure 8.15 – FTTx/VDSL energy consumption per subscriber in each access zone

The level of power consumption for FTTx/VDSL access areas is significantly higher compared to the other fibre-based choices, due to the cabinet contribution and the higher consumption of CPE equipment due to the usage of electrical signals instead of optical ones. This effect is progressively reduced over the years with the improvement of energy profiles in this equipment.

This enhancement translates into a lower impact of CPE in the total energy consumption. In this sense, local exchange consumption has a low impact on consumption as in GPON access networks due to the sharing of the devices' resources among customers.

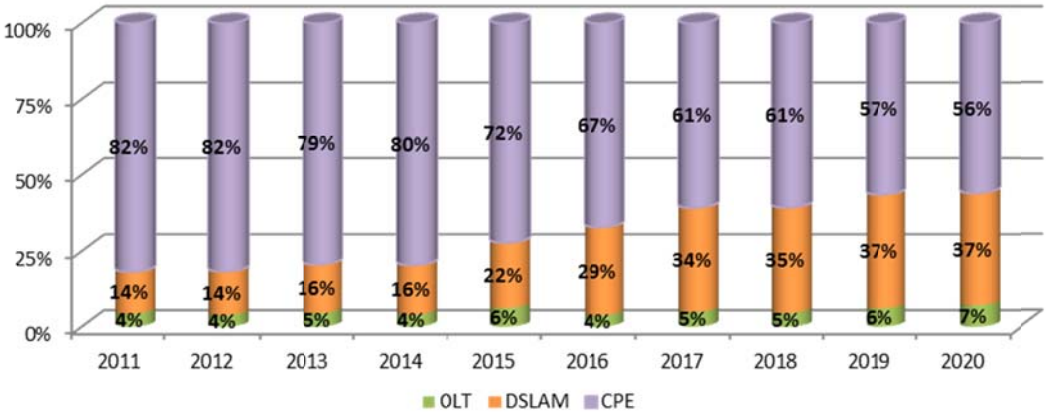


Figure 8.16 – Average energy consumption breakdown for FTTx/VDSL active devices (%)

Due mainly to the replacement of active devices occurring in 2017, the evolution of energy consumption falls after 2016. The same effects as found with the other two fixed technology choices occur again with this option, but the specific energy consumption profiles of DSLAMs modify the evolution regardless of the forecasted demand pattern.[51] A higher consumption level is achieved in the year 2016, reaching almost 0.9 million MW.

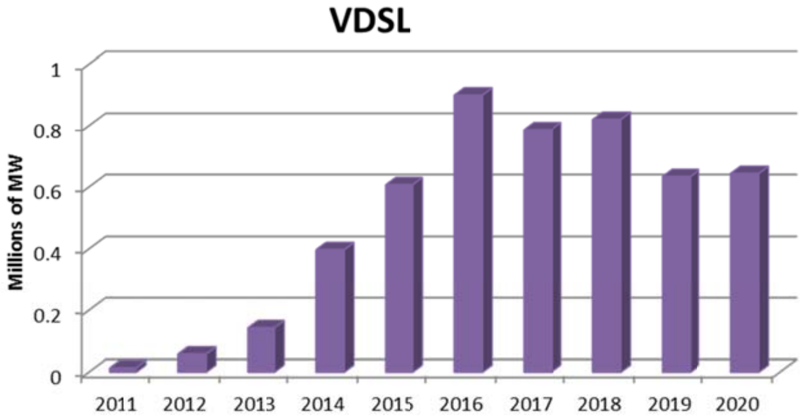
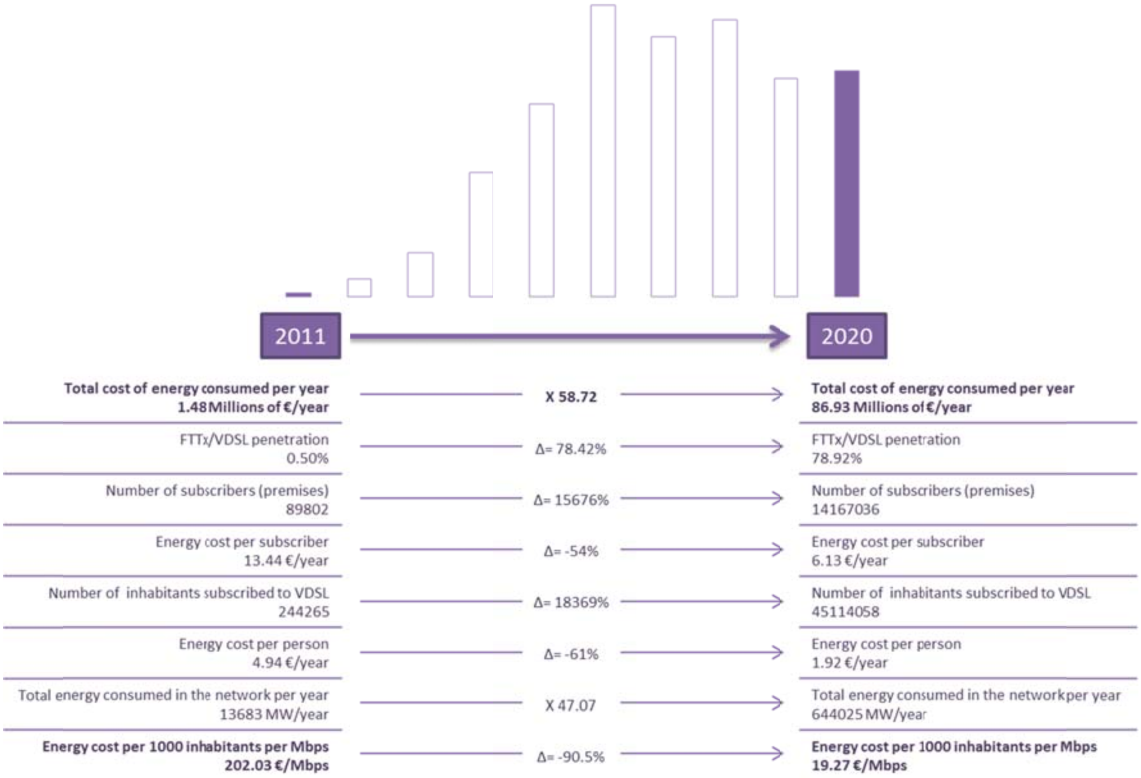


Figure 8.17 – FTTx/VDSL annual energy consumption profile

While the increase in the total cost of energy consumed is remarkable (almost 60-fold), the figure falls between the increases occurring in PtP (100-fold) and GPON (30-fold).



2011		2020
Total cost of energy consumed per year **1.48Millions of €/year**	X 58.72	**Total cost of energy consumed per year** **86.93 Millions of €/year**
FTTx/VDSL penetration 0.50%	Δ= 78.42%	FTTx/VDSL penetration 78.92%
Number of subscribers (premises) 89802	Δ= 15676%	Number of subscribers (premises) 14167036
Energy cost per subscriber 13.44 €/year	Δ= -54%	Energy cost per subscriber 6.13 €/year
Number of inhabitants subscribed to VDSL 244265	Δ= 18369%	Number of inhabitants subscribed to VDSL 45114058
Energy cost per person 4.94 €/year	Δ= -61%	Energy cost per person 1.92 €/year
Total energy consumed in the network per year 13683 MW/year	X 47.07	Total energy consumed in the networkper year 644025 MW/year
Energy cost per 1000 inhabitants per Mbps **202.03 €/Mbps**	Δ= -90.5%	**Energy cost per 1000 inhabitants per Mbps** **19.27 €/Mbps**

Figure 8.18 – Summary of FTTx/VDSL consumption and cost calculations

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[51] Although in the case of VDSL the pattern is not the same as in PtP and GPON, the profile is similar.

8.1.4.LTE

The difference between fixed and mobile energy consumption models that implies an additional stage in the mobile procedure is not the only one. As stated in the forecasting process description, customers using the two different options are not measured in the same way. In fixed networks, premises are accounted for, while in mobile networks the value of demand shows the number of inhabitants provided with ultra-broadband services. This implies that there are differences in the calculations, and therefore common units have to be used to provide a base framework for comparisons.

Starting with the analysis of cell energy consumption, Figure 8.19 shows the different profiles for the starting and the final year of the deployment.

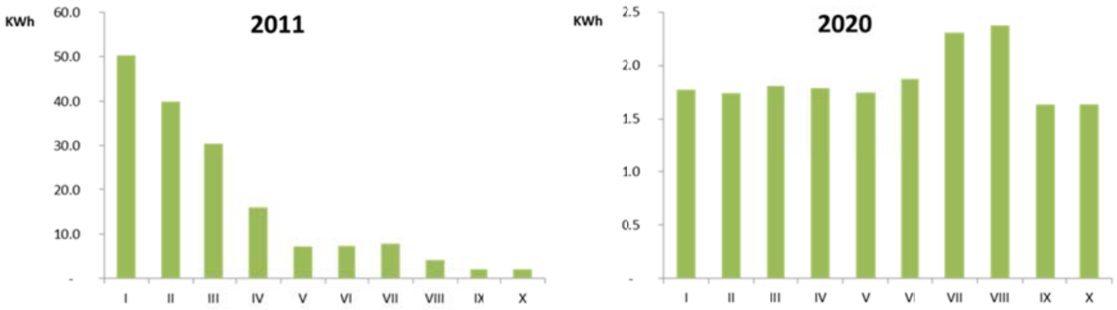


Figure 8.19 – LTE profile of energy consumption per cell for the initial and the final year of deployment

Femtocells consumption leads the power consumption, as can be shown in Figure 8.20, which precisely reflects the consumption profile of each cell, as the deployment of these devices is dependent on the density zone. The role of these devices in the last years of deployment decreases as the number of base stations required to be deployed increases considerably. Therefore the energy per cell in the last year is led by the base station consumption, which varies according to the density zone and increases as more radio links are needed, which is a function of the b geotype share. The level per cell decreases only in the two rural areas where no femtocells are required. In 2011 the lower level of consumption per cell (zones IX and X) is just 4% of the 50 KWh consumed by each cell in zone I. On the other hand cells in zone I consume 1.7 KWh in 2020, 75% of the maximum level found in zone VIII. It has to be considered that the cell sizing varies from year to year according to the specific data rate per user and also the available contention ratio.

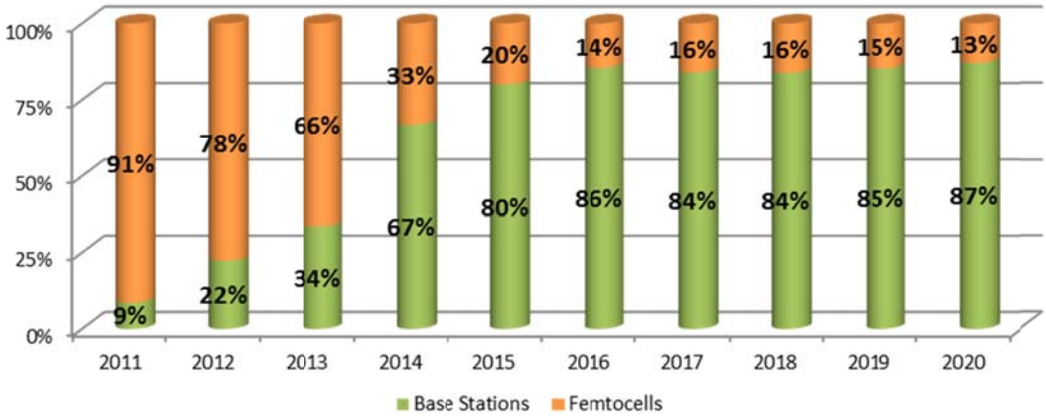


Figure 8.20 – Average energy consumption breakdown for LTE active devices

To determine a base framework for comparisons of the energy consumed by deployment units among technology choices, the values of energy consumed by the equivalent access area in LTE deployments are shown in Figure 8.21. While in the first year the consumption level is significantly lower than for fixed choices, the approximately four-fold increase during the deployment in areas I to VI translate into values just one third compared to the lowest access area's consumption in fixed access networks. In any case, in lower density areas the levels are approximately the same if not higher than in fixed deployments.

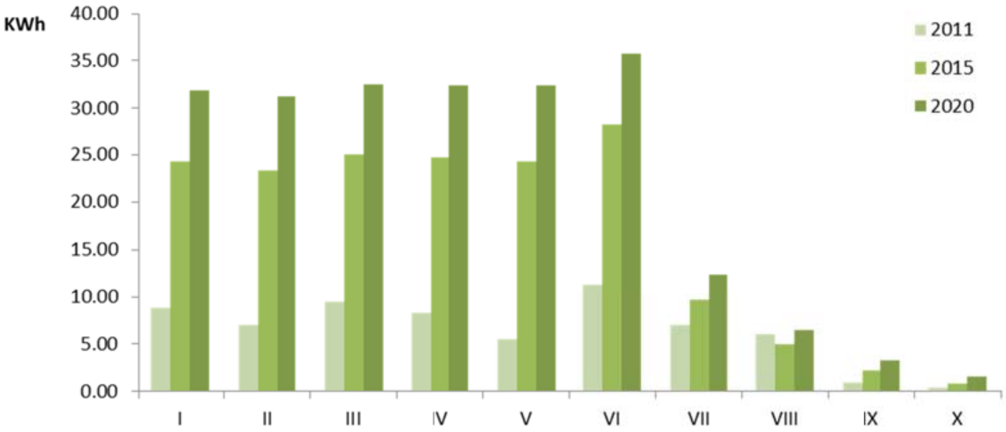


Figure 8.21 – LTE profile of energy consumption per access area for the year 2011

The profile of energy consumption of equivalent mobile access areas shown in Figure 8.22 defines the high impact of variation in the data rate per user along with the contention ratio, which is not so significant in fixed networks. A higher level is achieved in the year 2016, in which the provided level reaches 5 Mbps.

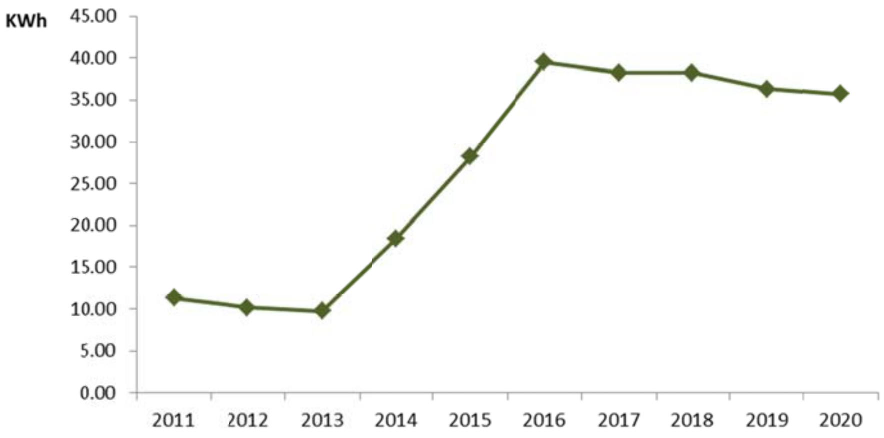


Figure 8.22 – LTE variation profile of energy consumption of a single access area in density zone VI for the period 2011–2020

This variation also has an effect on the energy per subscriber in each access zone. While the decrease is lineal in fixed networks, the behaviour in mobile access networks differs, even increasing the level per access area in high density zones.

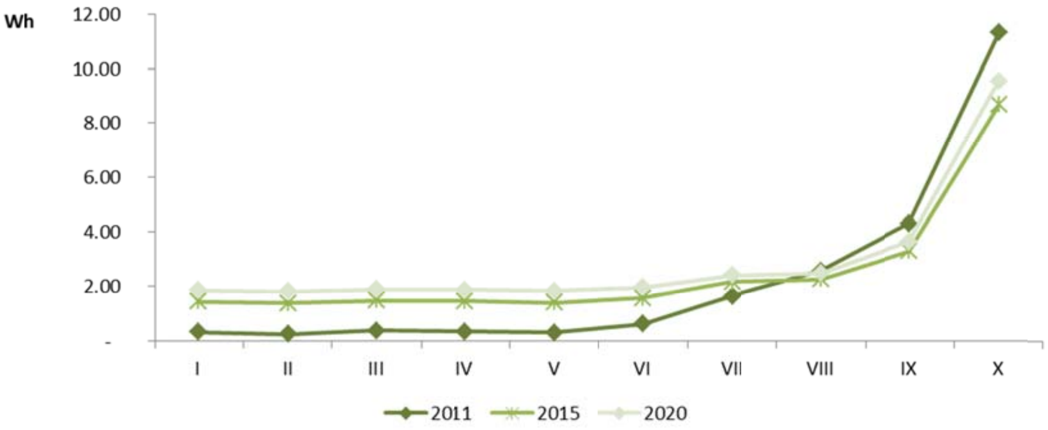


Figure 8.23 – LTE energy consumption per subscriber in each access zone

In the energy consumption profile, the effect of data rate increase and contention ratio reduction is more remarkable. In the year 2014, the interannual increase in energy consumption rises to 140% when the contention ratio goes down from 16 to 3 and the demand increases by 19% following the forecast performed. In the year 2016 a 57% rise in energy consumption also leads to the maximum level at 0.72 million MW. From that year onwards, three conflicting forces affect the energy consumption baseline for LTE: the improvements in technology (increase of spectral efficiency and more frequency bandwidth available), substitution of older equipment for more energy-efficient devices, and the continuation of 4G adoption. In 2020, a “mature” network energy consumption of 0.638 million MW is reached.

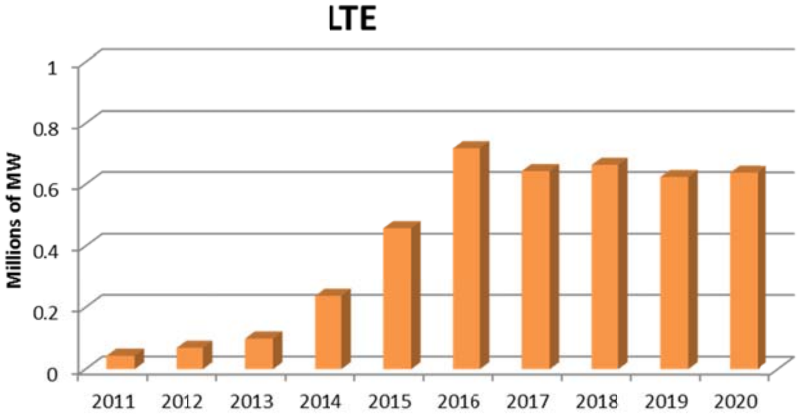
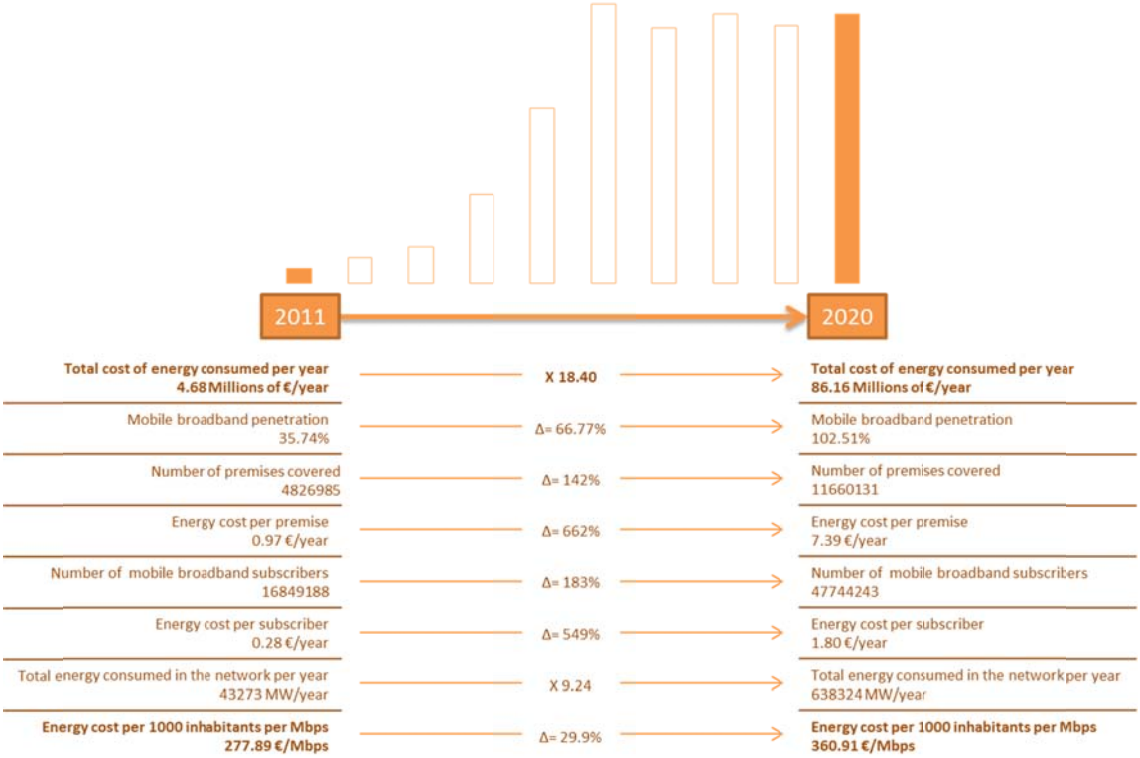


Figure 8.24 – LTE annual energy consumption profile

The situation for mobile broadband is rather distinct from the one for fixed broadband. Here, the total energy consumption and its costs increase considerably, but by a very modest proportion. This is essentially due to two facts: the network supporting mobile broadband is already partially deployed in 2012, and mobile technologies are, in general, much more scalable regarding deployment. These two facts also explain why the total cost of energy consumption in 2012 is higher for mobile technologies than for fixed choices (only comparable to VDSL level).

Regarding the demographic framework described, some implications emerge from the specific distribution of the density zones and the network sizing required in each one. In particular, mobile users and premises are more scattered in low density zones, making the sizing of the network more critical and the extra elements required per user more impactful on both energy consumption and costs. A different perspective is obtained when including the amount of broadband provided by the different technologies. In this case, the energy cost per megabit per second increases by 30% with respect to the starting year level while for all fixed networks this level decreases.



2011	Change	2020
Total cost of energy consumed per year 4.68Millions of €/year	X 18.40	**Total cost of energy consumed per year 86.16 Millions of €/year**
Mobile broadband penetration 35.74%	Δ= 66.77%	Mobile broadband penetration 102.51%
Number of premises covered 4826985	Δ= 142%	Number of premises covered 11660131
Energy cost per premise 0.97 €/year	Δ= 662%	Energy cost per premise 7.39 €/year
Number of mobile broadband subscribers 16849188	Δ= 183%	Number of mobile broadband subscribers 47744243
Energy cost per subscriber 0.28 €/year	Δ= 549%	Energy cost per subscriber 1.80 €/year
Total energy consumed in the network per year 43273 MW/year	X 9.24	Total energy consumed in the networkper year 638324 MW/year
Energy cost per 1000 inhabitants per Mbps 277.89 €/Mbps	Δ= 29.9%	**Energy cost per 1000 inhabitants per Mbps 360.91 €/Mbps**

Figure 8.25 – Summary of LTE consumption and cost calculations

8.2. COMPARISON BETWEEN TECHNOLOGIES

In both fixed and mobile cases, the deployment of basic coverage units is done with the aim of fulfilling the forecasted demand. The evolution in the number of these units for fixed (Figure 8.26) and mobile (Figure 8.27) networks is now analysed.

In fixed networks, the evolution is similar to the forecasted demand pattern, as the resources provided by the local exchanges can cope with the user demand in terms of data rate even with the assumed increase during the period. Therefore the growth in the number of deployed access areas decreases as the growth in the penetration does.

Figure 8.26 – Number of access areas deployed during the period 2011–2016 and annual growth

On the other hand the variation in the cells deployed is affected by the changes proposed in both spectral efficiency and bandwidth parameters occurring in 2017. In this year all the equipment needs to be renewed, so the coverage features vary significantly.

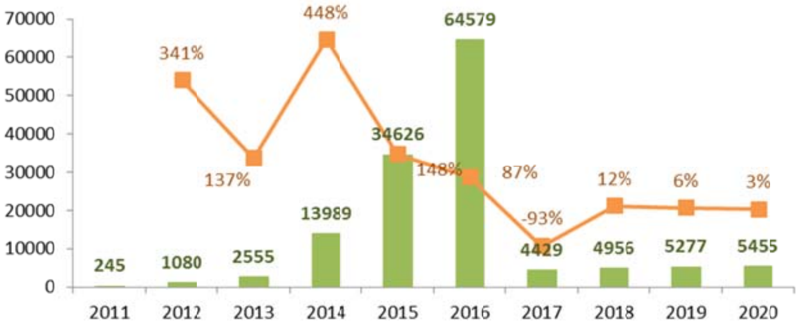


Figure 8.27 – Number of cells deployed during the period 2011–2016 and annual growth

Figure 8.28 summarizes the annual energy consumption profiles already discussed for each technology analysed to give a better visual comparison. The maximum level is achieved by FTTx/VDSL technology in the year 2016, but thanks to the energy efficiency improvements performed in the devices deployed the values at the end of the period are the lowest of all the choices.

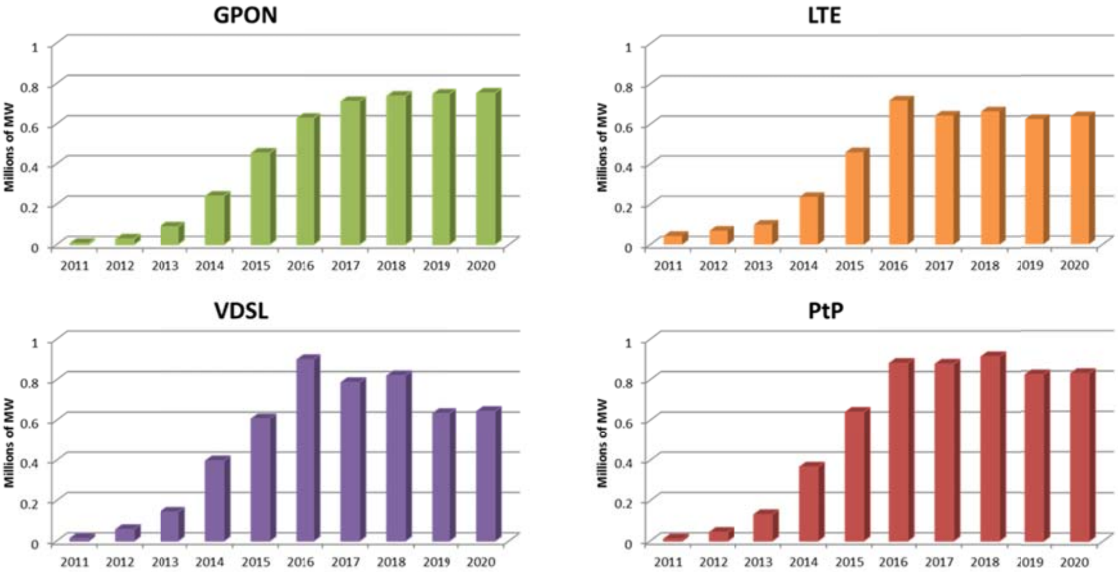


Figure 8.28 – Annual energy consumption profiles (millions of megawatts) for the different technologies

A completely different perspective is obtained when including the amount of broadband provided by the different technologies. In this case, the average energy per subscriber per megabit per second is approximately around two and a half times less in fixed than in mobile broadband technologies for the same QoS. These values can be used in sustainability comparisons among technologies and, more importantly, to reveal the effects of setting the QoS on the energy consumed in the network. This energy consumption profile in mobile access networks changes most significantly in 2013, 2015, and 2016, corresponding to modifications in the QoS to satisfy the increasing demand for broadband from subscribers.

The way in which it decreases over the period for all fixed technologies is also noteworthy. In these cases the impact of the variations in the data rate in 2016 and 2020 is more remarkable, highlighting the decreasing trend.

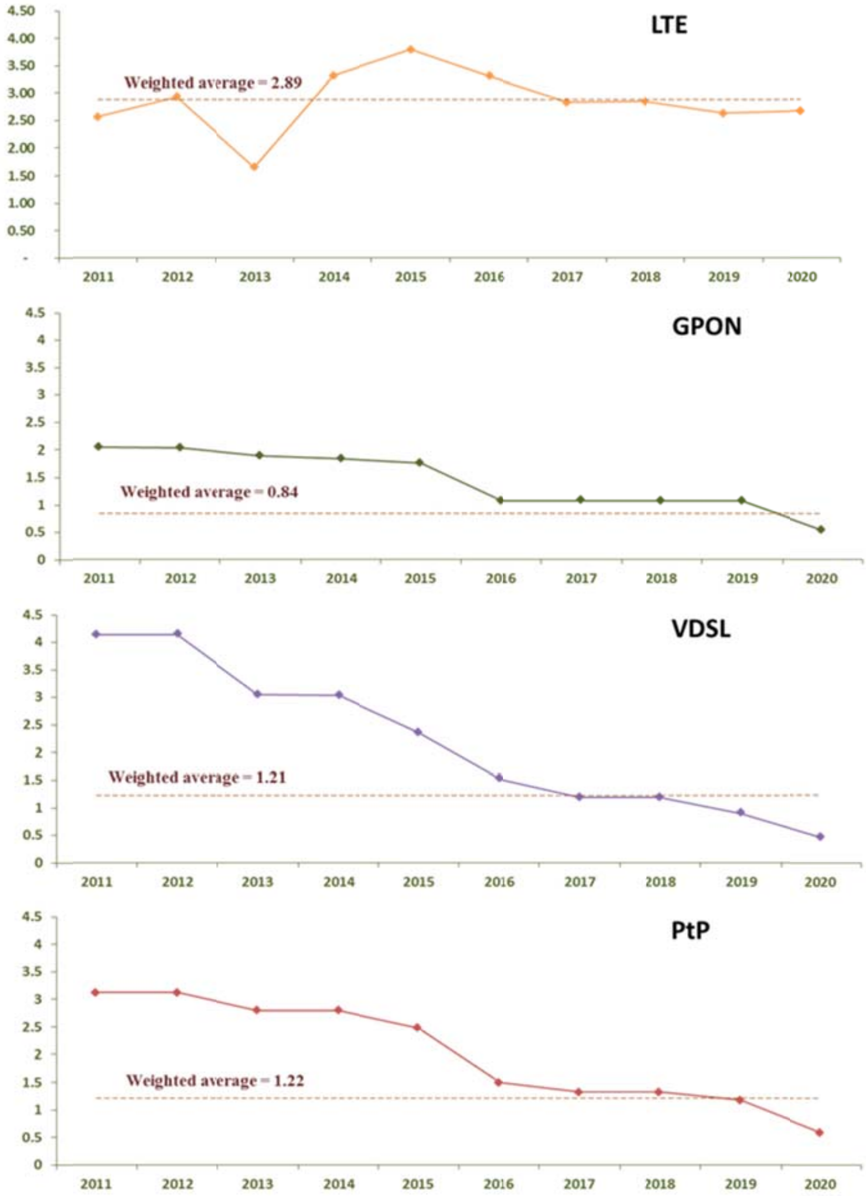


Figure 8.29 – Annual average energy consumption per subscriber and per megabit per second for each technology (kilowatts per year per megabit per second)

Finally the total consumption due to each technology for the complete deployment period is presented in Figure 8.30.

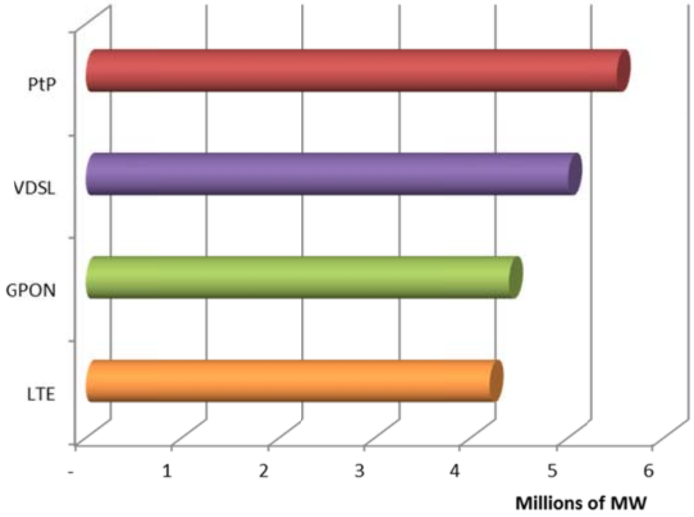


Figure 8.30 – Total energy consumption (millions of megawatts) for the different technologies

The PtP network requires more investment in energy resources, but mainly due to the second half of the deployment period. This evolution is depicted in Figure 8.31.

In the first year of deployment the consumption in mobile networks is substantially higher than for the other fixed choices. This is due to the already mentioned lower level of initial deployment of fixed networks compared to mobile ones. Nevertheless due to the higher scalability of mobile networks in half of the period, VDSL and PtP options accumulate more consumption than the other two choices. From this year until the end of the period, a series of changes occurs in the network parameters. This translates into LTE having the lowest power consumption of the four choices. For PtP, due to the lack of scalability, the accumulated energy consumption grows much more than for the rest of the technologies. GPON and VDSL are based on sharing infrastructures; along with the enhancements in energy profiles, this helps in maintaining energy consumption figures at similar levels to those of the mobile technology.

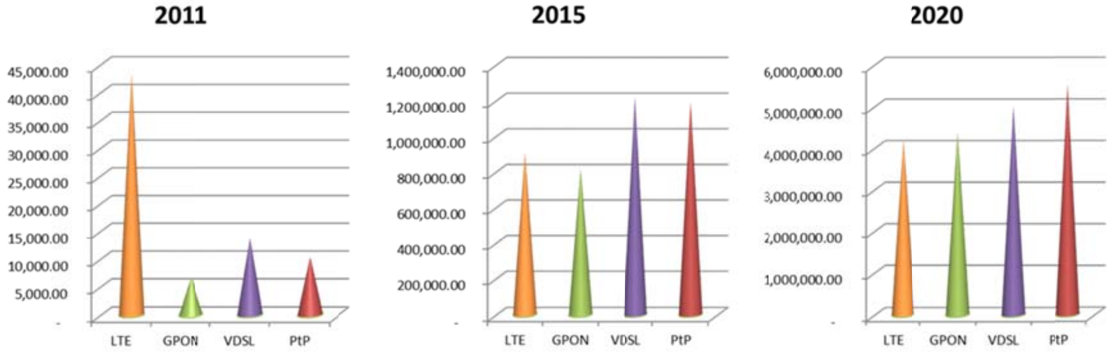


Figure 8.31 – Evolution of accumulated energy consumption (MW) for the different technologies in the years 2011, 2016, and 2020

8.3. CUSTOMER DEVICES

The model presented for assessment of the energy consumption of customer devices delivers a series of results. The idea is to compare the access networks' consumptions in the first and the final year of deployment with those of the user devices distributed for both fixed and mobile technologies according to the assumptions made in Chapter 7.

First, regarding the importance of each device in the consumption level, Figure 8.32 depicts the devices' specific roles.

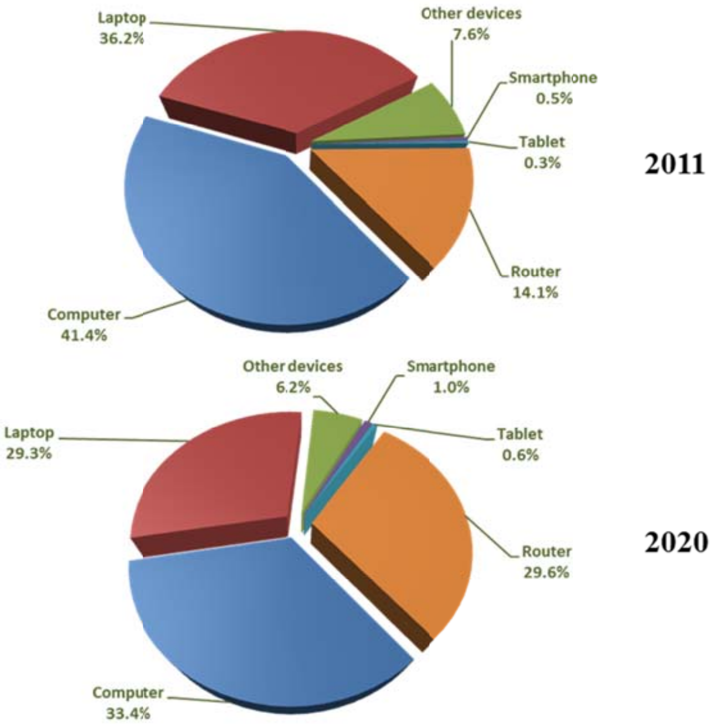
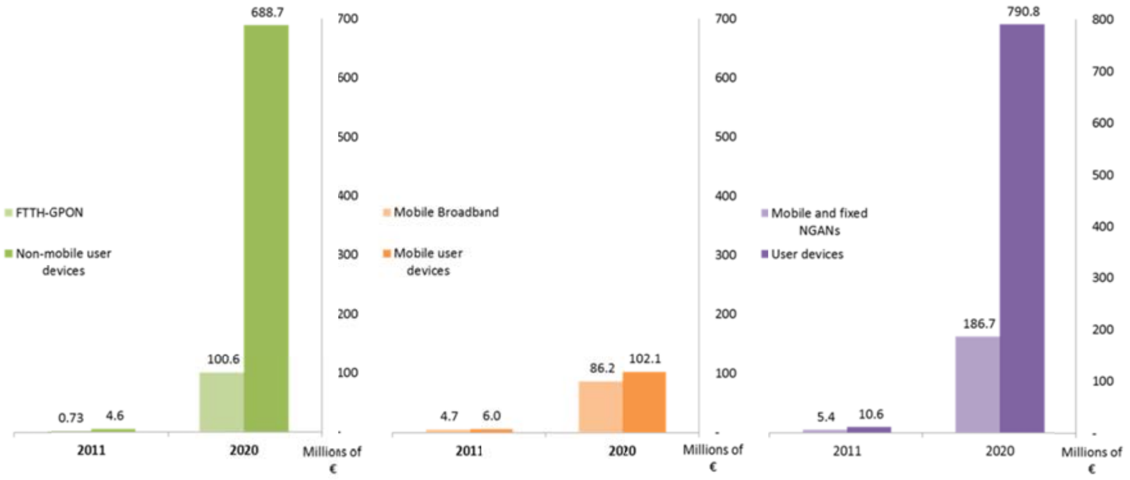


Figure 8.32 – Breakdown of energy consumption of customer devices for 2011 and 2020

Computers and laptops together account for around 70% of the consumption in the first year. In 2020, only the increase in the number of routers allows this set of devices achieving a similar level of total energy consumption than that of computers or laptops in 2020. The low consumption profiles of mobile devices reflect their importance in the energy consumption levels. Even with the increasing trend of using mobile devices (smartphones and tablets) following the mobile data traffic evolution, their role is still modest in the last year of the period.

Comparisons are made between the access network energy consumption levels of FTTH-GPON and LTE with fixed and mobile sets of devices respectively, according to demand levels. For the complete scenario, both fixed and mobile levels are added as if the two networks coexist in the demographic scenario.

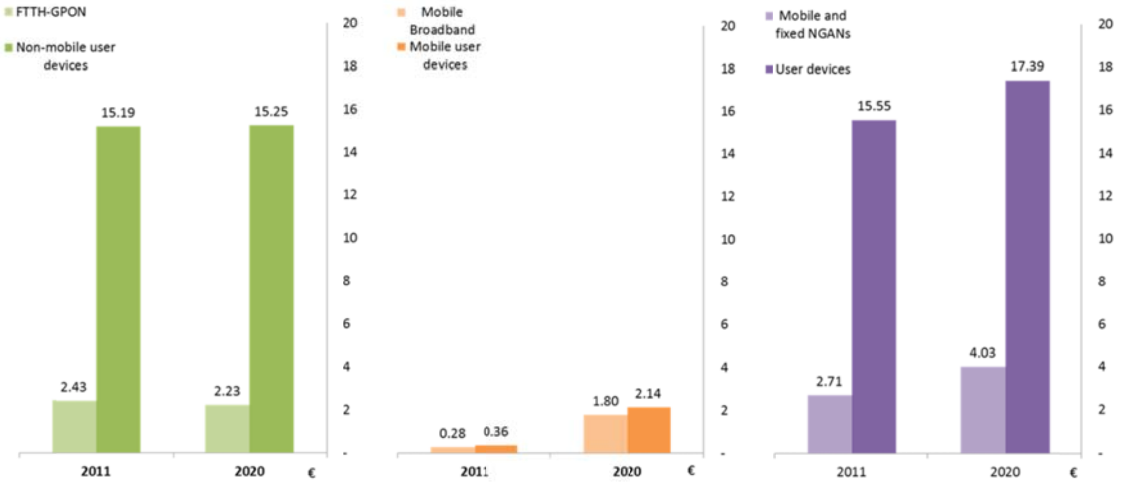
Figure 8.33 compares the baseline results of the costs of energy consumption within the NGNs with those of user devices. When comparing network consumption and user devices, there are again important differences between fixed and mobile technologies. User devices typically attached to fixed broadband networks are projected to consume almost seven times more energy than the network itself in 2020. In the mobile broadband case, the network and device energy consumption levels and cost levels are projected to be closer, both at the start of the analysis period in 2011, when the devices' consumption cost is 28% higher, and in the year 2020, when it is 18% higher. The total aggregated usage of fixed and mobile networks with respect to the breakdown of traffic between the two types of networks—considering Wi-Fi offloading—is depicted in part (c) of Figure 8.33. While in 2011 the cost of energy consumed by NGNs was two times lower than that consumed by user devices, this ratio is projected to increase slightly to 4.23 by 2020, indicating in both cases the sheer predominance of energy consumption (and cost) associated with user devices. It is also worth noting that while routers are responsible for about 10% of fixed user device consumption, this proportion increases to 70% in the case of mobile user devices via traffic offloading.



(a) (b) (c)

Figure 8.33 – Cost of energy consumption (M€) in 2011 and 2020 in (a) FTTH-GPON vs. non-mobile devices; (b) mobile broadband vs. mobile devices; (c) fixed and mobile NGNs vs. user devices

When the calculations are performed per subscriber (Figure 8.34), the situation is logically the same: "plugged" user devices consume more than their wireless counterparts in terms of network consumption, and the device portion of the aggregated cost for users due to energy consumption is considerably higher than the network energy consumption. The ratio of device to network energy consumption is projected to decrease slightly between 2012 and 2020, although it is still projected to remain more than four times higher.



(a) (b) (c)

Figure 8.34 – Cost of energy consumption per subscriber (€) in 2012 and 2020 in (a) FTTH-GPON vs. non-mobile devices; (b) mobile broadband vs. mobile devices; (c) fixed and mobile NGNs vs. user devices

8.4. RESULTS FROM THE DEMAND CALCULATION FORECAST

The different forecasting methods defined in Section 5.3.3 are now compared. The exercise is done only for LTE technology.

Figure 8.35 shows the baseline for the annual energy consumption per subscriber from 2011 to 2020 obtained by the three forecasting methods as well as the total annual consumption. Both the average consumption per subscriber and the total annual energy consumption are rather similar for all the forecasting models. Using the Bass model (11.23 KW/year) for the baseline, the Logistic average consumption is only 0.9% higher, and the Gompertz level is only 3.2% lower than the baseline. The energy consumption evolution profiles for the three models are also similar. However, these profiles exhibit various interesting features. The energy consumption per subscriber in 2016 shows a significant increase (of almost 70%) over the 2015 levels. This is a year in which the market is still increasing considerably but without technical advances, and only a limited spectrum is available. The energy consumption per subscriber decreases after the allocated bandwidth and the spectral efficiency improve in the following year (2017). This effect holds until 2019 when the improvements in the energy efficiency dominate the decreasing demand growth rates. In 2020, the market is finally more mature, and the growth in the usage and therefore in the energy consumption is not compensated for by improvements, likely calling for another cycle of innovations in energy efficiency.

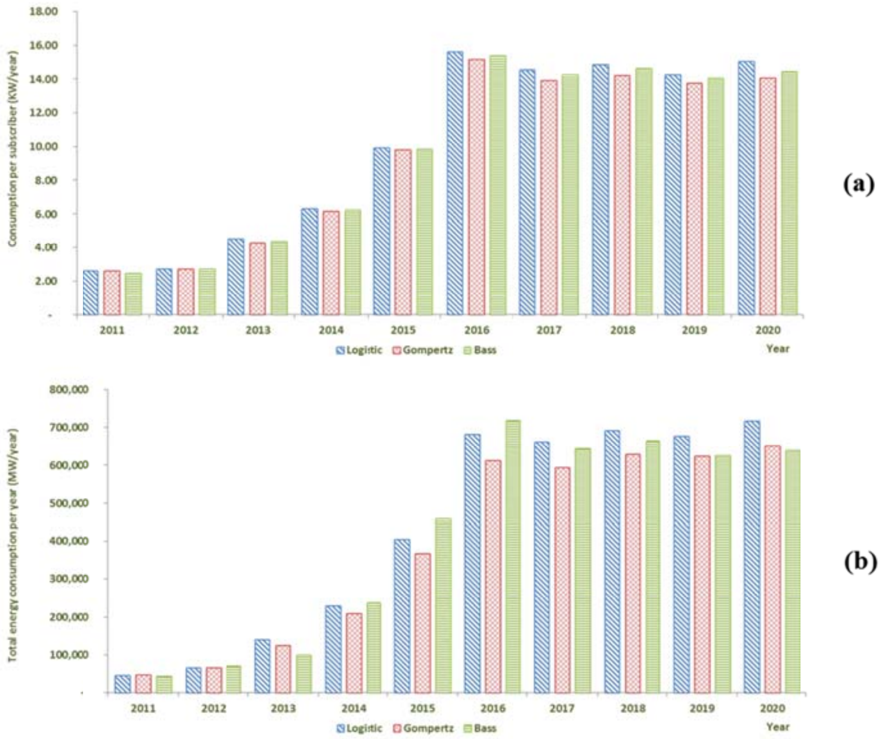


Figure 8.35 – (a) Annual energy consumption per subscriber in mobile broadband networks and (b) total energy consumption per year (megawatts per year) from 2011 to 2020 in Spain

The baseline also shows that the total energy consumption for mobile broadband increases by different total amounts (by 14 to 20 times from 2011 to 2020) depending on the forecasting process used. This is due to the need to scale up the network to cater for more subscribers and more intense usage, both of which increase the number of base stations, the picocells/femtocells, and their workload. However, the total energy consumption already departs from some relevant values, shows a steep initial growth, and plateaus relatively rapidly. This behaviour can be attributed to two factors: the partial deployment of the network supporting mobile broadband in 2011–2012 and the high scalability of the mobile technologies in terms of deployment and therefore energy consumption.

The total cost of energy consumption for the complete period therefore varies according to the forecasting process. Nevertheless from the initial choice of logistic curve the variation existing with the other possibilities is nearly 4.7% higher than with the Bass model and 9.6% higher than with the Gompertz model. While important, these variations are modest compared to other potential changes in other parameters.

8.5. ECONOMIC IMPACT OF ENERGY CONSUMPTION

The use of the assessed energy resources results associated costs. To perform the transformation of energy to costs, the values presented in Section 4.2 are used, using the consumption levels for each year. When compared with the operational expenses associated with the access network deployed, these costs give a sense of the impact of energy consumption on the economic expenditure required to maintain the access network and also on the overall costs associated with its deployment.

The first step includes the analysis of the evolution of the energy-related cost for every technology during the deployment period. This variation is similar to that of the energy consumption previously reviewed.

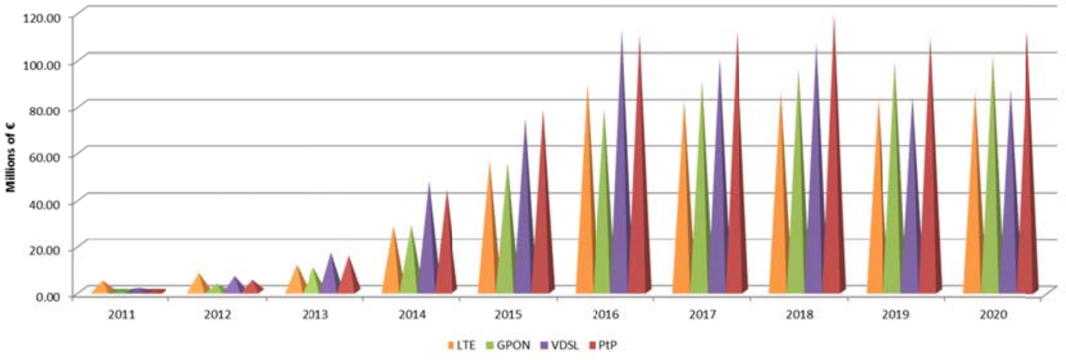


Figure 8.36 – Total costs of energy consumption per technology

In any case the total accumulated cost of energy during the 10-year period is depicted in Figure 8.37. PtP technology appears to be the most expensive technology in energy terms, requiring 31% more investment in this issue than the LTE choice.

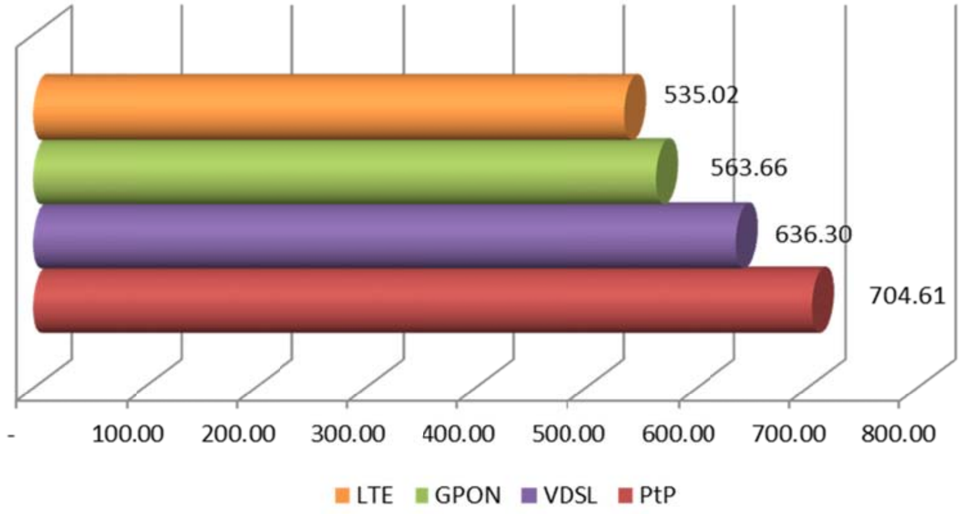


Figure 8.37 – Accumulated costs of energy consumption (millions of euros) for the 10-year deployment period

If the costs per premise (subscriber) or per person are considered, it is also noteworthy that they decrease in FTTH-GPON despite the increase in energy prices. The reason is that in fixed networks the devices' consumption depends directly on the number of subscribers served by the network and evolves with this number. In the case of mobile broadband, the evolution of the energy consumption per subscriber is the opposite in comparison to FTTH-GPON: the cost of the energy almost quadruples in the period considered, as the network has to scale up to cater for more subscribers and more intense usage, with both factors increasing the number of base stations, pico/femtocells, and their workload.

Total costs are lower for mobile broadband technologies compared to FTTH-PtP (29.8% higher) and FTTH-GPON (17.9% higher), and only 0.9% lower than those for FTTx/VDSL at the end of the period.

Interestingly, the case would be completely different without considering improvements in spectral efficiency and an increase in the spectrum bandwidth allocated to mobile operators. Without these improvements, the cost of energy consumption for the LTE network in 2020 would be € 205.8 million, more than two times the cost of the energy consumed in the mobile broadband baseline scenario.

Finally, a completely different perspective is obtained when including the amount of broadband provided by the different technologies. In this case, the energy cost per megabit per second is approximately 16 times less for FTTH-GPON than for mobile broadband technologies in 2020.

To complete the portrait of energy consumption costs, the next set of results compares these energy costs with operating expenses.[52] See Section 0 for details on the calculation of the latter.

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[52] No data for PtP technology are derived from the cost analysis so this technology is left out of this part.

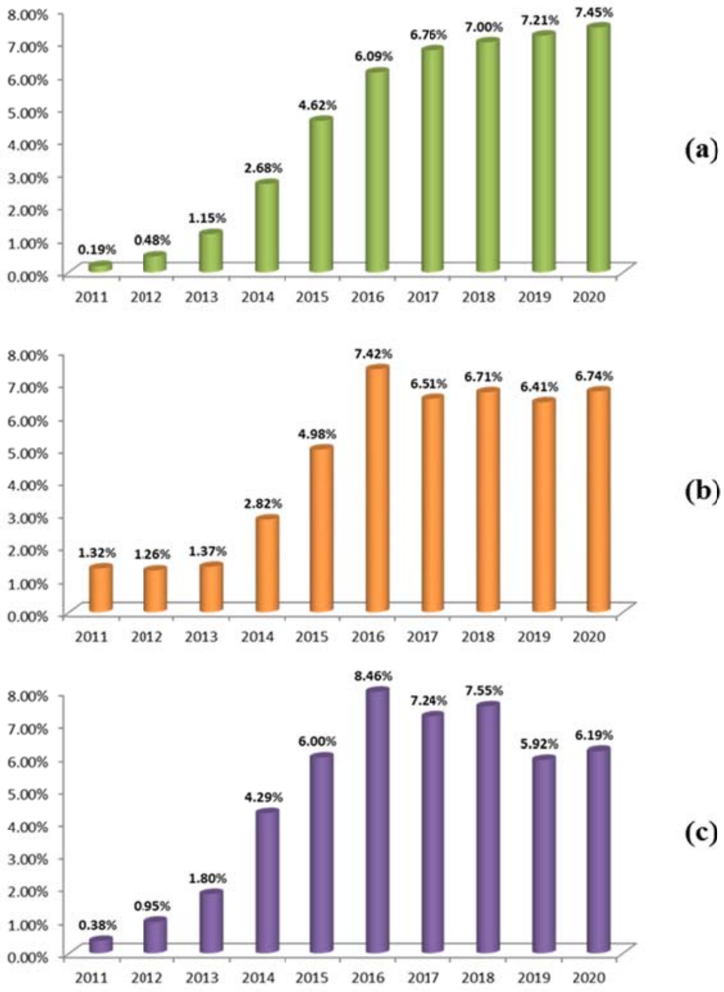

Figure 8.38 – Percentage of annual energy cost compared to operating expenses in the period 2011–2020 in (a) FTTH-GPON; (b) LTE; (c) FTTx/VDSL

In 2020, the annual energy cost as a percentage of operating expenses is 7.45% for LTE, more than 0.75% higher than the percentage for FTTH-GPON, and 1.26% higher than that for FTTx-VDSL.

As for the energy costs compared to total investment required for network deployment and maintenance during the period analysed, the energy cost represents 2.57% of the related network expenses for FTTH-GPON, 3.46% for FTTx-VDSL, and 3.49% for LTE technology.

In mobile technologies, low demand variation in the last years results in lower required capital expenditures and therefore energy consumption cost reaches a peak of 7.2% of the 2020 network related investment. In FTTH-GPON the peak value, 3.4%, also appears in 2020, and in FTTx/VDSL it comes in the second year of deployment, reflecting 5.8% of the expenditure figures.

8.6. SENSITIVITY ANALYSIS

Now a sensitivity analysis is performed. Alternative scenarios departing from the baseline are considered for possible improvements in the management of networks as well as other roadmaps for achieving energy efficiency in network devices. Every one of the scenarios presenting potential variations is considered separately. Even though the model allows these variations to be combined, the analysis aims at determining the impact of each of them on its own, and it is assumed that no special correlation between them is present.

The sensitivity analysis is done regarding the economic impact of the variation of the selected variables. In this way the analysis of a possible variation in the energy price can also be included.

Multiple parameters have been described in the energy consumption model. Some of them apply to both fixed and mobile technologies, while others affect only one of the groups. In the next figure all the parameters selected for this analysis are depicted and grouped according to their areas of effect.

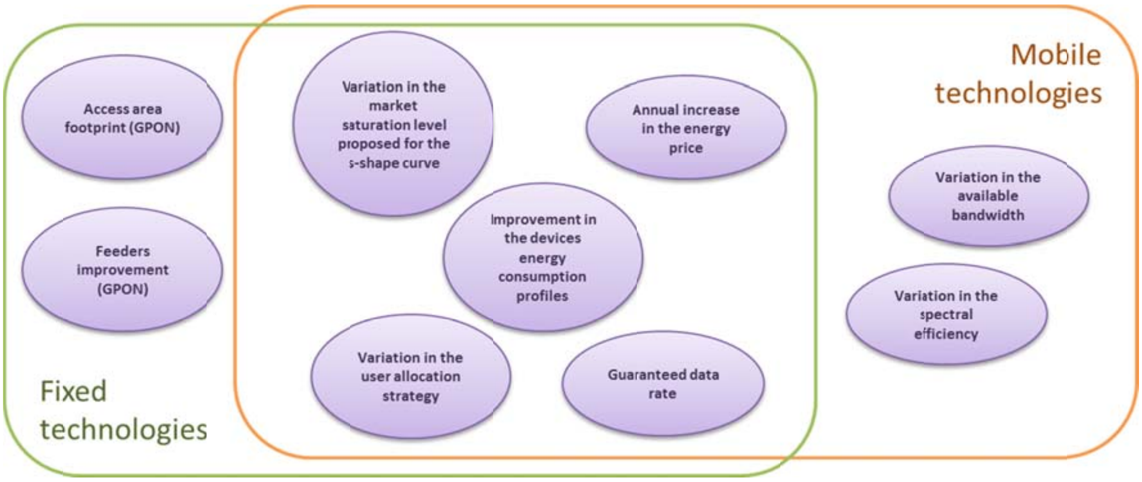

Figure 8.39 – Parameters for the sensitivity analysis

- **Variation in the energy price**

Without affecting the level of energy consumed, the variation of this value between years has a significant impact on the cost related to the energy required. These changes affect each technology assessment equally.

A scenario with no price variation determines a 10% reduction in the implied costs. Other possibilities, such as 1 and 3% instead of the 2% assumed in the baseline, are included. Finally, if the increase is doubled (4% annual variation) each year, an 11% increase in the total cost has to be faced.

- **Subscriber allocation strategy variation**

As mentioned in the baseline scenario (Section 0), the allocation of subscribers attending to specific constraints can occur. Whether the deployment target is focused on the low density areas or the high density areas, or on a rapid or slow deployment pace, significantly affects the total amount of energy consumed during the years.

The baseline results are based on a choice of deployment strategies that corresponds to the operators' maximum return on investment. However, this approach is not the only possible strategy. Due to regulatory conditions or the influence of public subsidization, the deployment may begin from a lower-density area. Note that due to the costs of deployment this would make sense mainly for mobile networks.

If the strategy is modified, mobile broadband consumption in 2012 would be 3.6 times higher. However, the difference between the two strategies in 2020 in terms of cost would only be 7.8%. This small final difference shows that in both cases each deployment is near completion at the end of the period. However, the profile of energy expenditure in arriving at this final stage is very different, and hence a 40% variation in total cost appears.

In fixed technologies, consumption in the first year increases by 9% for FTTH-GPON and 17% for FTTx/VDSL, while there is no variation for FTTH-PtP. Due to the particularity of the PtP deployment, the strategy selected does not impact the energy consumed, due to the constant profile of consumption for every user in every density zone. The modification of the strategy results in a 4% increase for FTTH-GPON and a 14% increase for FTTx/VDSL.

- **Energy profiles of active devices**

The variation in the energy consumed by active devices is obtained from the guidelines presented in the EC Code of Conduct. Therefore this part assesses the impact that the evolution of the energy profiles of network devices will have if they are not performed as assumed.

Two alternative scenarios are proposed: in the first only half of the improvements in energy efficiency are performed; in the second no enhancements with respected the initial 2011 values are done.

Regarding sensitivity analysis, in PtP networks the special nature of the network design data rate per subscriber variation impacts on the deployment investment required rather than on the energy consumed, as this is affected mainly by the interfaces' consumption. If the improvement in energy profiles of these interfaces were not effective, the cost of the energy consumed in the network would increase by 23%.

This variation affects FTTx/VDSL technology more, as it is due to the improvements done in this area that the energy does not reach higher figures when the deployment achieves higher penetration rates. Without enhancements in the energy profiles, the cost will go up by 131%. On the other hand, in this situation the cost increases by 40% for FTTH-PtP and by 22% for both FTTH-GPON and LTE.

- **Market saturation changes**

The levels of market saturation used in the forecasting processes define the shape of the curve of the evolution/growth process to reach these specific values. As discussed in the demand calculation section (5.3.3), the market saturation levels are chosen exogenously. Changes in the levels selected, which can be caused by many constraints related to broadband markets, result in modifications of the penetration levels calculated for each year of the period.

A small variation of ± 10% in the market saturation level in the first step of the demand forecasting process was chosen for the analysis. The rationale behind this choice is that the subscribers' mobile market is already mature, exhibiting well-known dynamics that are not expected to change significantly until 2020. On the other hand the NGAN fixed market is in its incipient stage so many potential changes can occur during the deployment period. In either of the two cases, changes in this parameter considerably impact the energy consumption.

Figure 8.40 shows the variation in the number of lines/subscribers according to variations in the market saturation level.

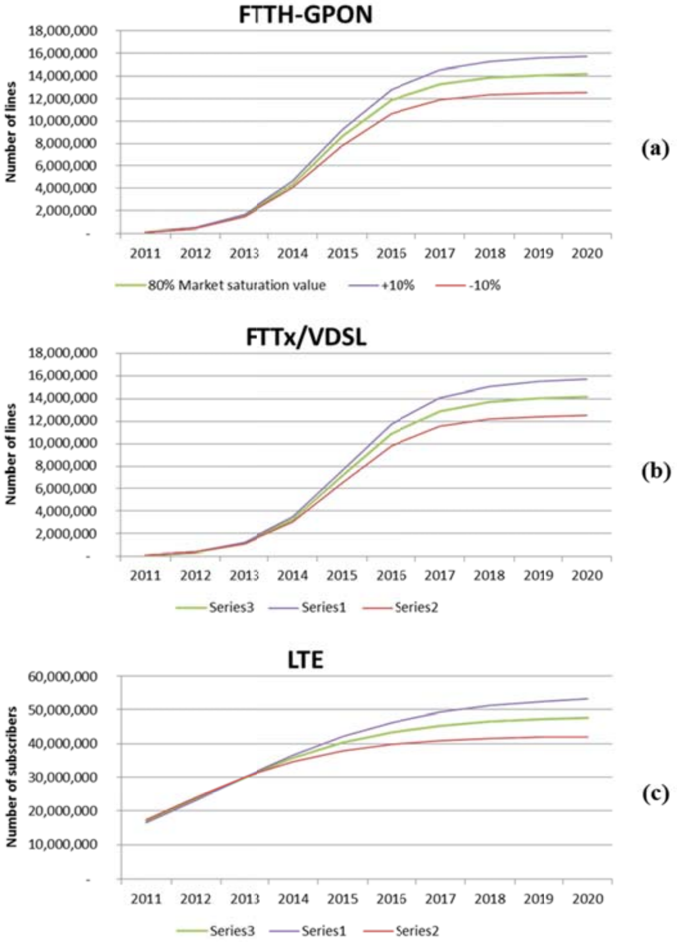

Figure 8.40 – Variation of forecasted demand according to market saturation changes in (a) FTTH-GPON; (b) FTTx/VDSL; and (c) LTE

This variation has an almost linear impact at least for the variation values proposed.

- **Variation in the initial guaranteed data rate**

The modification of the starting value of guaranteed data rate impacts significantly on the deployment costs, but what will happen to the level of energy consumed?

The value for mobile technologies changes from 1 to 5 Mbps and that for fixed ones from 30 to 100 Mbps. In fixed networks, the variation of the subscriber data rate from 30 to 50 Mbps would have an effect on the energy consumed, increasing it by 1%, whereas as a critical parameter in the mobile network design the impact of this variations is considerably higher.

- **Variations in FTTH-GPON networks sizing and local exchanges**

Variations in the GPON access area footprint will not have significant consequences. In fact if too many subscribers are covered when more subscribers are present in each access area, the power required by the local exchange increases, and therefore an excessive increase in this factor could result in higher total consumption.

Likewise the improvement of local exchanges' feeders does not have significant consequences, even multiplying the capacity by four due to the low level of importance of this active device within the total energy consumption of each access area.

- **Variation in the available bandwidth (BW) and spectral efficiency level (mobile networks)**

A variation of ± 5 bps/Hz is proposed in the spectral efficiency level of the baseline scenario. The spectral efficiency is expected to improve by 2017. The sensitivity analysis shows that if this development does not occur, the total energy consumption increases by 16.7%.

In the case of BW, a double/half scenario is proposed. An increase in the effective spectrum bandwidth available to mobile network operators for 4G from 20 to 40 MHz in 2017 is also considered in the baseline. Without this critical augmentation in the spectrum, it would be necessary to increase the total energy consumption in the network by 52%. Other scenarios were also analysed, with variations in the BW of 10, 30, and 40 MHz compared to the 20 MHz baseline value.

If the two effects are combined, that is, if no improvements in the spectral efficiency are made and the spectrum bandwidth allocated to mobile operators increases, the total energy consumed in the network would almost double, proving the relevance of both technical and policy developments.

- **Variation in the base station management**

According to the network usage pattern, there are specific times during the day in which lower network resources are required. If network management solutions were available, base stations could be controlled in order to cease operations without affecting customers and network performance. Specific scenarios, in which one out of three and one out of four base stations are switched off at night, are analysed, concluding that this measure can positively affect the energy consumption levels decreasing them in around 10–15%.

The next table summarizes all the results obtained from the sensitivity analysis.

Table 8.1 – Summary of the results derived from the sensitivity analysis

Alternative assumption		**Variation of energy cost from baseline (%)**			
		FTTH-PtP	**FTTH-GPON**	**FTTx/VDSL**	**LTE**
Costs of energy	Remain constant	-10%			
	Increase 1% annually	-5%			
	Increase 2% annually	0% (Baseline)			
	Increase 3% annually	5%			
	Increase 4% annually	11%			
Deployment strategy	From high to low density	0% (Baseline)	0% (Baseline)	0% (Baseline)	0% (Baseline)
	From low to high density	0%	4%	14%	48%
Device energy enhancements	According to guidelines	0% (Baseline)	0% (Baseline)	0% (Baseline)	0% (Baseline)
	Half the goal of guidelines	7%	9%	23%	10%
	No enhancements at all	40%	23%	131%	22%
Market penetration limit	+10%	9%	9%	11%	12%
	-10%	-10%	-11%	12%	-11%
Guaranteed data rates (QoS)	Reaching 100 Mbps in fixed networks in 2017	0.4%	0.4%	0.4%	-
	Not reaching 100 Mbps in 2020 (staying at 50 Mbps in fixed networks from 2016 onwards)	-0.0%	-0.0%	-0.0%	-
	Staying at 3 Mbps in mobile networks from 2015 onwards	-	-	-	-17%
	Staying at 2 Mbps in mobile networks from 2013 onwards	-	-	-	-30%
Access area footprint (in number of subscribers)	+200%	-	-0.4%	-	-
	+100%	-	-1.4%	-	-
	+50%	-	-1.3%	-	-

Alternative assumption		**Variation of energy cost from baseline (%)**			
		FTTH-PtP	**FTTH-GPON**	**FTTx/VDSL**	**LTE**
Improvements in GPON technology (from 2017 onwards)	10 Gb/s fibre feeders	-	0% (Baseline)	-	-
	40 Gb/s fibre feeders	-	-1.3%	-	-
BW allocated (from 2017 onwards)	No additional spectrum	-	-	-	52%
	10 MHz additional spectrum	-	-	-	17%
	20 MHz additional spectrum	-	-	-	0% (Baseline)
	30 MHz additional spectrum	-	-	-	-10%
	40 MHz additional spectrum	-	-	-	-17%
Spectral efficiency (max.) (from 2017 onwards)	15 b/s/Hz	-	-	-	17%
	20 b/s/Hz	-	-	-	0% (Baseline)
Improvements in management systems of mobile communications	Switching off one in four base stations at night	-	-	-	-11%
	Switching off one in three base stations at night	-	-	-	-14%

9. CONCLUSIONS AND FURTHER RESEARCH

9.1. CONCLUSIONS

Energy considerations have played a very limited role in the planning, management and regulation of NGNs. This seems incomprehensible, considering that broadband networks are the centre of any policy or strategy for boosting economic development and as "the establishment of ultra-high-speed networks is often seen as the basis for realization of the great potential for social and economic change related to ICT" (Røpke, 2012). If the future is to be sustainable and NGNs are to have a role to play in that future (Noam, 2013), then the energy consumption of NGNs–and its related cost—must not be overlooked. In the case of operators, energy consumption costs have a direct impact on their operating expenses, but promoting sustainable innovation strategies could become an import criterion for stakeholders beyond the mere business plan. In addition, citizens are ever more conscious of their role in the building of the society, trying to add their two cents to making it more sustainable. For many of them, energy-saving aspects are becoming a factor to be considered in consumption decisions, at least for some product and services. Although this behaviour has not yet been shown to extend to telecoms, it is worth of exploration, if only to increase user awareness of the energy relevance in the ultra-broadband networks domain.

Paradoxically in the current information society, in general, consumers and even policy-makers lack of specific information and therefore know little or nothing about the energy impact of the increasing usage of telecommunication networks. Thus, these groups are missing critical information with which to make informed decisions. There are no studies in the telecom industry to corroborate this assertion, but the similar issue of green electricity has been analysed further. Potential adopters of green tariffs are found to be better informed on energy matters, are concerned about the environment and believe that individual actions can affect environmental degradation (Diaz-Rainey & Ashton, 2011). Information is a recurring factor in these analyses. For instance, Stall-Meadows and Hebert (2011) conducted experiments in which informing participants about the energy efficiency, sustainability and associated costs of several types of lighting considerably increased the participants' preference for adopting the higher-priced sustainable lighting. All of the above evidence shows that although environmental matters are far from being cutting-edge issues in current telecom markets, duly marketed "green strategies" may nonetheless be productive. Therefore, the absence of information conflicts with the rise of a new class of consumers who are making conscious and knowledgeable choices.

In fostering the discussion about the energy efficiency of telecommunications networks, this research introduces a model for the assessment of the energy consumed by next generation access networks in a dynamic and changing practical setting. The baseline for assessing the consumption has been constructed by combining a series of network related design parameters and three main forecasts: the evolution of active devices in the network, the data traffic per subscriber, and the mobile broadband demand. Additionally a trace on the evolutionary process of the access network deployment is included.

Each of these forecasts uses a particular methodology: technical prospective, scenario building, growth models, and strategic planning respectively. Thus, a main result of the research is that different methods must be combined for complex forecasts, such as energy consumption methods, in which technical design and developments must be blended with specific user behaviour and aggregated demand. Nevertheless considerable simplifications have been made to obtain a baseline that illustrates real scenarios but, at the same time facilitate distinct sensitivity analyses, thus arriving at practical conclusions. Note also that because there were not relevant real data available for comparison with the results obtained, the assumptions in the baseline were given special relevance to ease replicability.

Moreover the baseline is also useful for determining the telecommunications demand alone. The demand variations in markets, such as the mobile telecommunications, are of paramount importance for network operators who rely on these prospective calculations to justify the considerable investment required to ensure the availability of the services provided (Fildes & Kumar, 2002). In this sense the research proposes a methodology for demand calculation regarding the different technology types, exploring in turn different approaches. While the variations derived from the different solutions are not to be neglected, the impact of the specific solution regarding the demand issue is in general lower than that of other parameters.

The baseline also shows the importance of technological and policy enhancements to reduce consumption in communications. The obvious first solution to achieve a higher degree of energy efficiency is to improve the energy profiles of the devices scattered along the network rollout. This can be accomplished through a continuation of existing policies concerning energy-efficient network devices. In fact, here an extension of the existing guidelines through 2020 is proposed. Also, although there was an obvious effect projected to result from increasing the energy efficiency of network devices, their precise impact in the deployment of main NGAN access technologies remained largely unexplored. The analysis of the baseline quantifies the costs of the absence or delay in the adoption of such guidelines, providing a foundation for further policy making and highlighting two important points: the relevance these developments have and the positive impact of achieving, as quickly as possible, the goals established in the guidelines.

Anyway, other factors that influence energy consumption in the access network portion could have also significant influence. In particular, the technological features of networks, such as the spectral efficiency and frequency bandwidth allocated to mobile operators, strategic decisions such as QoS, market penetration, and the size and order of coverage for areas in the deployment can substantially influence energy consumption and its evolution over the period leading up to 2020. The effects of these technological developments and strategic decisions have been neglected in assessments of energy efficiency and sustainability perspective, despite the fact that they could have a huge impact. The case of frequency bandwidth allocated to mobile operators is paradigmatic: it is the factor with the single greatest influence on the costs of energy consumption, although it is seldom mentioned, if at all, among the motivations for freeing spectrum and harmonizing spectrum-related policies. The proposed baseline quantifies the precise effect of additional spectrum on energy savings, permitting a detailed assessment of policies in this field. In addition, within the mobile domain, improvements in spectral efficiency and management of cellular systems have considerable impact, suggesting research goals (for private companies and public bodies) with a measurable impact on sustainability, and, in the case of management systems, providing an incentive for a different type of infrastructure sharing among operators.

In fact, and in general, deviations from the baseline have more consequences for mobile networks; fixed networks are less sensitive to deviations that may occur, for example, when considering changes in the deployment strategy to cater to rural areas, changes in the QoS, or even when specific modifications in the fixed technology or topology of the network are considered. The reason behind this lesser sensitivity is simple. The energy consumption of fixed networks depends basically on the ONT at the consumer premises (except for FTTH-PtP technology due to its particular characteristics already detailed), and its evolution remains stable, except when energy guidelines are not followed. On the other hand the energy consumption of mobile networks is basically dependent on the number of base stations and their features, parameters that are deeply modified in alternative scenarios. As a consequence, in fixed networks, the key element for further improvements is the ONT, which can be modified without major changes in the network design. However, in mobile networks, the critical element is the design of the network itself and its main component: the base station, both of which are linked with a priori strategic decisions for operators, and is highly sensible to modifications on demand specifications.

Among other assessments the baseline explicitly evaluates two main indicators of network sustainability: the annual energy consumed per subscriber and the annual energy consumed per subscriber per Mbps. These figures can serve as a reference to evaluate whether technological progress, economic evolution and policy decisions are able to progress beyond the "normal" situation and contribute to, or worsen, sustainability. When considering consumption on the user side, the results show that the energy used in fixed networks is higher than in mobile networks within the baseline described. However, if the cost of energy per subscriber per Mbps is considered, FTTH-GPON is considerably more efficient, and therefore under this perspective, this technology is more sustainable. Deployment strategies have also a huge impact on the energy consumption profile during deployment stage. Additionally this will set the conditions for the consumption during the maturity stage.

When user devices are considered, the baseline departs from a relatively balanced situation in 2011, where the aggregated consumption of energy in the network and user devices has a relatively similar level (regarding matching penetration rates). However, this share of energy changes dramatically over the years to a situation where the consumption of user devices exceeds in almost one order of magnitude the consumption in the network. It is usually accepted that energy usage in ICTs is shared in three relatively similar parts: servers, networks and devices (ITU, 2007; Sutherland, 2009). However, the evolution of NGNs will modify the balance, reducing the share of the network and proportionally increasing that of the devices.

Nonetheless, this shows that reductions in the energy consumption of user devices would have a much greater impact than increasing the efficiency of the network ones, in addition to the benefit of reducing users' direct energy costs. In this regard, while there are specific guidelines for a roadmap on the energy efficiency of network devices, there are not equivalent specifications on the user device side with similar broad industry agreement. Routing equipment appears to be a main target of energy efficiency improvements, because of its key role in managing both fixed data traffic and off-loading of mobile data traffic. This is, therefore, an area of policy making with industry support.

Along the same lines, IEA indicates that global residential electricity consumption by ICT equipment grew by nearly 7% per annum between 1990 and 2008, and even with foreseen improvements in energy efficiency, consumption from electronics is projected to increase by 250% by 2030 (IEA, 2009). All of these results underscore the relevance of implementing technical, economic and policy strategies that do not discourage the use of ultra-broadband technologies but rather make them more energy efficient, including the energy consumption of user devices in the equation.

All in all, the resulting baseline hints at various enhancements that could be implemented to reduce the level of energy consumption by NGANs. In this sense overall policy has a considerable influence in the energy consumption regarding these upcoming networks. Some key parameters regarding network design depend on regulatory decisions, such as the already mention portion of the available spectrum allocated to operators. Policy also influences the rollout strategies of access networks in a number of ways, license conditions and subsidies being two prominent examples. Moreover, guidelines for energy efficiency depend on policy initiatives to gather industry support. Furthermore, policies establish roadmaps for research into energy-efficient technologies. Last but not least, energy policies affect the cost of energy consumption in ultra-broadband networks and thus retail prices for consumers. In each of these policies it is possible to pursue more sustainable avenues, e.g., increasing spectrum allocation to mobile operators, balancing license conditions with measures to save energy, influencing industry compliance with guidelines for energy efficiency in network and user devices, and including more specific sustainability goals in research and development public programmes. As a particular instance of the lack of policy action in public institutions regarding energy consumption in telecoms networks, it could be mentioned that "IEA is aware of the importance of energy consumption related to running the ICT infrastructure […] but no specific policies are suggested …" (Røpke, 2012).

A final point to be made is that the piece of information about the energy impact of their increasing usage of networks and devices, and their associated costs and effects on sustainability, is normally a missing point in most of the deployment plans of telecommunication networks. Developing accurate models, like the one described in this research, to achieve knowledge about this factor, will surely help defining an extra criterion to make informed decisions, and to add a comparative factor in the process of selecting the more convenient technology and network design in specific scenarios under perspectives beyond the mere economic investments required.

Against this background, this research has attempted to place energy considerations in the forefront of the debate and, has shown that providing thorough and transparent information on the usage of ICT networks, and other related issues (economic impact of energy consumption, user devices…), is feasible and relevant.

9.2. FURTHER RESEARCH

During the first steps of this research project, many uncertainties arose around which were the necessary tools and subjects to approach in order to build up a simple but yet thorough and adaptable model. The model has to be applicable to different technologies and scenarios and to meet the typical changes in this evolving industry. The foundations were laid around the analysis already done on the deployment economics, leveraging the demographic data research, the access network architectures, or the network sizing configurations used in this former stage. This step also aims to enquire about the architectural complexity of the different technologies, thus identifying the consuming devices included in each access network deployed and their coverage features.

These initial steps led to the development of a basic energy consumption model for a single year, which allows the potential energy consumption values of a complete demographic scenario network deployment to be determined. This was done by disregarding possible variations and taking many assumptions on certain parameters to the limit in order to obtain a maximum threshold.

The logical next step was to understand the parameters that vary over time with the purpose of developing suitable patterns and to integrate them in the initial consumption model. After a thorough analysis, the conclusion obtained was that different methods must be combined, which is a complex task in which technical design and developments must be blended with specific particularities such as user behaviour or aggregated demand evolution.

While the models depicted here allow a fairly accurate assessment of the energy consumption to be obtained, increases in accuracy can be achieved in many ways. In fact, there are some parameters whose evolution can modify the energy consumed during any time period analysed and that, if included in the models, will surely improve their accuracy.

To begin with there is the case of the demographic changes of the country in the case study, including the total population, the age distribution, and the urban/rural distribution. Demographic changes relevant to this study are assumed to be small over the time period considered. The possible significant variations, due to migrations from rural to urban areas or out of the country, for example, affect the distribution of users across the scenario. All these changes will in fact directly affect the target penetration figures and the population allocated to each zone, altering the number of subscribers and hence modifying the number of active devices to be deployed.

Also regarding the demographic scenario some enhancements of the distribution procedure can be done. These can be based on the fact that in a practical deployment cases the optimal trenching topology should be calculated by some—typically heuristic—procedure (Casier et al., 2008) that takes into account exact data on central offices, location of existing ducts for potential reuse, and customer location for each town and municipality.

The research proposes an average profile for network usage, although this parameter can be modelled for the diverse density zones and even for the different days of the week or for any other time fraction of the year. Changes may appear as a result of variations in, for example, the users' habits depending on economic, educational, or other factors beyond the design of the network or on other usage conditions such as pricing over the different hours of the day. Likewise, variations in user behaviour with regard to network usage can arise due to the impact of data capping and pricing on access network energy consumption.

The deployment strategies observed try to cope year by year with the figures obtained from the demand forecasting exercise. Even though the scenario is not unrealistic at all—considering that operators usually deploy the network pilots in high density selected locations—more complex approaches can be proposed. For instance deployments in the selected scenario disregarding the density characteristic (i.e. covering a particular autonomous region, province, …) could also be plausible alternatives. This will translate into more complex distributions of the subscribers over the years. Additionally the coverage targets may have to be updated dynamically due to specific requirements of each zone, therefore affecting the deployments.

Moreover, the assessment done takes into account the deployment of access networks separately, without considering the natural interaction of several infrastructures. Therefore potential competition scenarios may appear not only in the selection of the optimal technology for each demographic zone but also in the way operators would partake in the infrastructures deployment in each zone.

Regarding mobile technology, the parameters with more impact on the network design, bandwidth, and spectral efficiency could benefit from a more technical analysis. This is due, for example, to the existing discontinuity of their effective values throughout each cell or the specificity of the terrain, which ultimately determines and models the particular distribution and values available (Mogensen et al., 2007). As a matter of fact the use of different frequency bands determines particular propagation schemes affecting the QoS of the provided services that should be reviewed. All these modifications will result in changes in the coverage features and therefore in the network sizing.

In other matters, a comparison of resulting energy consumption figures derived from the model performance with those of the actual telecom infrastructures seems necessary. Addressing this task has proved to be a complex challenge due to the lack of transparency regarding this issue from the operators and related industry side. In any case, information on not only the energy consumption but also the specificities of existing deployments, such as the number of existing base stations across the covered scenario, among others, can help to perform a sanity check on the results obtained.

Finally, it worth noting that in the approach followed, the effects of the diverse evolution processes are accounted for separately, disregarding the possible effects that could appear if they were combined. The possibility of indirect effects of the evolution of one parameter on that experienced by another is not far from reality and should be analysed in future researches.

In any case the model developed can serve as a benchmark for other developments not considered, such as deeper modifications of network topology, new modulation schemes and protocols, and further variations in network management systems, as suggested in the technical literature (Ajmone Marsan & Meo, 2011; López Vizcaíno et al., 2012).

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ANNEX I – ADDITIONAL TABLES

DEMOGRAPHIC SCENARIO TABLES

Table Annex 0.1 – Demographic and economic data (INE(1), 2010; INE(2), 2010)

Zone	*Population (inhabitants)*	*Percentage of the total population*	*Surface (km^2)*	*Percentage of the total surface*	*Population density (inh/km2)*	*GDP per capita (2008)(€)*	*Rate to the national GDP level*	*Total GDP (2008)(€)*	*Contribution to Spain GDP*
Andalucía	8302923	17,76%	87597,71	17,31%	94,78	18.507	77%	148.710.898	13,60%
Aragón	1345473	2,88%	47720,25	9,43%	28,2	26.323	109%	34.088.269	3,10%
Asturias (Principado De)	1085289	2,32%	10603,57	2,10%	102,3	22.559	93,90%	23.752.804	2,20%
Balears (Illes)	1095426	2,34%	4991,66	0,99%	219,45	25.967	108%	27.334.601	2,50%
Canarias	2103992	4,50%	7446,95	1,47%	282,53	21.105	87,90%	43.248.707	3,90%
Cantabria	589235	1,26%	5321,34	1,05%	110,73	24.508	102%	14.027.720	1,30%
Castilla Y León	2563521	5,48%	94225,96	18,62%	27,21	23.361	97,30%	58.067.761	5,30%
Castilla-La Mancha	2081313	4,45%	79461,97	15,71%	26,19	18.471	76,90%	36.448.165	3,30%
Cataluña	7475420	15,99%	32113,41	6,35%	232,78	28.095	117%	202.805.851	18,60%
Comunitat Valenciana	5094675	10,90%	23254,52	4,60%	219,08	21.468	89,40%	105.554.211	9,70%
Extremadura	1102410	2,36%	41581,98	8,22%	26,51	16.820	70,10%	18.033.734	1,70%
Galicia	2796089	5,98%	29574,38	5,85%	94,54	20.619	85,80%	56.290.249	5,20%

Zone	*Population (inhabitants)*	*Percentage of the total population*	*Surface (km^2)*	*Percentage of the total surface*	*Population density (inh/km2)*	*GDP per capita (2008)(€)*	*Rate to the national GDP level*	*Total GDP (2008)(€)*	*Contribution to Spain GDP*
Madrid (Comunidad De)	6386932	13,66%	8027,69	1,59%	795,61	31.110	129%	193.477.917	18,00%
Murcia (Región De)	1446520	3,09%	11313,11	2,24%	127,86	19.692	82,00%	27.943.667	2,60%
Navarra (Comunidad Foral De)	630578	1,35%	10390,36	2,05%	60,69	30.614	127%	18.544.139	1,70%
País Vasco	2172175	4,65%	7235,13	1,43%	300,23	32.133	133%	68.281.522	6,20%
Rioja (La)	321702	0,69%	5045,25	1,00%	63,76	25.895	107%	8.033.559	0,70%
Ceuta	78674	0,17%	19,48	0,00%	4039,37	22.320	92,90%	1.611.846	0,20%
Melilla	73460	0,16%	13,41	0,00%	5476,62	21.493	89,50%	1.494.776	0,10%
Spain	**46745807**	**100,00%**	**505938,13**	**100,00%**	**92,39**	**24.020**	**100%**	**1088502000**	**100,00%**

Table Annex 0.2 – Regional evolution of broadband penetration (subscriptions per 100 households) in Spain (INE(3), 2010)

Zone	*2004*	*2005*	*2006*	*2007*	*2008*	*2009*	*2010*	*2011*	*2012*
Spain	14,7	21,1	29,3	39,2	44,6	51,3	57,4	61,9	66,7
Andalucía	11,5	17,1	24,2	35	38,9	46,3	52,9	56,2	63,1
Aragón	15,3	20,1	29,7	39,9	45,2	50,8	58,3	62,7	67,8
Asturias (Principado de)	15,8	25,5	32,3	38,9	47,7	51,2	58	62,4	67,1
Balears (Illes)	22	25,5	34	44,8	49,9	58,2	64,3	66,5	71,5
Canarias	16,1	23,8	35	42,5	45,4	52,9	56,6	60,5	64,6
Cantabria	15	20,7	32	41,9	49,4	55,2	56,9	65,7	68
Castilla y León	9,7	16,7	23,8	32,5	34,8	41,1	47,1	54,2	62,4
Castilla-La Mancha	8,6	13,1	20,7	28,3	36,3	43,8	51,9	57,5	61,6
Cataluña	19,4	26,9	36,6	46	52,5	60,5	67,2	69,3	70,6
Comunitat Valenciana	14,8	19,3	24,3	36,7	42,5	46,9	52,1	59,6	60
Extremadura	7,2	10,8	16,3	23,2	35,3	39,4	45,9	52,2	57,9
Galicia	9	13,8	19,4	25,7	31,8	38,3	46,5	51,6	62,3
Madrid (Comunidad de)	19,9	28,1	39,6	51,7	57,9	62,6	65,9	71,4	77,3
Murcia (Región de)	12,7	16,8	25,8	31,5	35,8	44,4	51,2	59,3	63,8
Navarra (Comunidad Foral de)	10,8	17,2	26,6	40,1	44	52,4	58,8	63,1	68,2
País Vasco	14,7	23,2	29,5	40	43,7	55,2	63,2	64,9	71,4
Rioja (La)	10,3	17,9	26,2	37,4	45,1	48	54,6	58,1	64,5
Ceuta	23,1	32,7	37,2	46,2	46	45,6	61,2	65	70,2
Melilla	12,6	21,2	39,2	47,7	45,9	50,8	65,8	59,3	64,8

Table Annex.0.3 – Summary of demographic data for Spain (2001 for population and households, 2009 for businesses). Source: INE (2004, 2009)

Zone	***I***	***II***	***III***	***IV***	***V***	***VI***	***VII***	***VIII***	***IX***	***X***	***Total***
Population density	***>10 000 hab/km^2***	***10- 5 000 hab/km^2***	***5 - 3 000 hab/km^2***	***3 - 1 000 hab/km^2***	***1 000 - 500 hab/km^2***	***500 - 100 hab/km^2***	***100 - 50 hab/km^2***	***50 - 10 hab/km^2***	***10 - 5 hab/km^2***	***< 5 hab/km^2***	
Number of municipalities	17	28	46	175	209	946	745	2705	1444	1797	**8112**
Total population	2 707 360	6 300 119	3 832 203	8 596 709	5 016 333	11 326 891	3 574 008	4 406 394	668 735	317 055	**46 745 807**
Population per municipality	159 256	225 004	83 309	49 124	24 002	11 973	4 797	1 628	463	176	**5 763**
% of national population	5,79 %	13,48 %	8,20 %	18,39 %	10,73 %	24,23 %	7,65 %	9,43 %	1,43 %	0,67 %	**100 %**
% of national population (acc)	5,79 %	19,27 %	27,47%	45,86 %	56,59 %	80,82 %	88,47 %	97,90 %	99,33 %	100 %	**100 %**
Total surface (km^2)	179,14	1 086,33	969,99	5 278,55	7 103,38	50 561,39	52 638,58	185 348,40	92 937,96	108 573,47	**504 677,19**
Surface per municipality	10,54	38,80	21,09	30,16	33,99	53,45	70,66	68,52	64,36	60,42	**62,21**
% of national surface	0,04 %	0,22 %	0,19 %	1,05 %	1,41 %	10,02 %	10,43 %	36,73 %	18,42 %	21,49%	**100 %**
% of national surface (acc)	0,04 %	0,26 %	0,45 %	1,50 %	2,91 %	12,93 %	23,36 %	60,09 %	78,51 %	100 %	**100 %**
Population density (h/km^2)	15 113	5 799	3 951	1 629	706	224	67,9	23,8	7,20	2,92	**92,63**
Number of buildings	150.991	349.457	292.268	1.001.308	768.534	2.546.655	1.195.033	2.088.085	517.713	374.469	**9 284 513**

Zone	***I***	***II***	***III***	***IV***	***V***	***VI***	***VII***	***VIII***	***IX***	***X***	***Total***
Population density	***>10 000 hab/km^2***	***10- 5 000 hab/km^2***	***5 - 3 000 hab/km^2***	***3 - 1 000 hab/km^2***	***1 000 - 500 hab/km^2***	***500 - 100 hab/km^2***	***100 - 50 hab/km^2***	***50 - 10 hab/km^2***	***10 - 5 hab/km^2***	***< 5 hab/km^2***	
Inhabitants per bulding	17,93	18,03	13,11	8,59	6,53	4,45	2,99	2,11	1,29	0,85	**5,03**
Buildings density (b/km^2)	842,87	321,69	301,31	189,69	108,19	50,37	22,70	11,27	5,57	3,45	**18,40**
Number of households	956.677	2.076.924	1.170.050	2.509.817	1.406.991	3.106.774	1.056.207	1.486.870	273.065	143.794	**14.187.169**
Persons per household[53]	2,63	2,74	2,95	2,88	2,91	2,96	2,93	2,78	2,55	2,37	**2,85**
Number of businesses[54]	247.676	536.081	311.978	709.653	400.875	880.898	270.780	330.552	50.376	24.361	**3.763.229**
Number of households and businesses (n_{user})	1.204.353	2.613.005	1.482.028	3.219.470	1.807.866	3.987.672	1.326.987	1.817.422	323.441	168.155	**17.950.398**
Households and businesses per building	7,82	7,34	4,96	3,14	2,29	1,53	1,08	0,85	0,61	0,44	**1,89**
Multi-dwelling units	110.542	236.055	146.786	395.617	254.702	678.233	274.232	383.016	72.718	49.757	**2.601.658**
% of total buildings	73%	68%	50%	39%	32%	27%	23%	18%	14%	13%	**28%**

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[53] INE data only gives number of households with 1, 2, 3, 4, 5, 6 and 7 or more persons. The figures in the table have been obtained supposing a maximum number of 7 persons per household

[54] Businesses per municipality are obtained from businesses per province distributed proportionally to the population of the municipality. This approach includes the number of different locations for the same business.

Zone	***I***	***II***	***III***	***IV***	***V***	***VI***	***VII***	***VIII***	***IX***	***X***	***Total***
Population density	***>10 000 hab/km^2***	***10- 5 000 hab/km^2***	***5 - 3 000 hab/km^2***	***3 - 1 000 hab/km^2***	***1 000 - 500 hab/km^2***	***500 - 100 hab/km^2***	***100 - 50 hab/km^2***	***50 - 10 hab/km^2***	***10 - 5 hab/km^2***	***< 5 hab/km^2***	
Single-unit buildings	40.449	113.402	145.482	614.181	542.133	1.833.646	921.000	1.706.285	442.955	323.816	**6.683.349**
% of total buildings	27%	32%	50%	61%	68%	73%	77%	82%	86%	87%	**72%**

Table Annex.0.4 – Number of potential subscribers to NGAN as a function of geotype. Source: own estimations from INE (2004, 2009) and Ministerio de Vivienda (2007)

Geotype	***Total potential subscribers (households + businesses)***	***Total population***	***% of potential subscribers and population per zone***
Ia (> 10 000 inh/km2)	1.021.201	2.295.639	85%
Ib (> 10 000 inh/km2)	183.152	411.721	15%
IIa (10-5 000 ihn/km2)	1.643.385	3.962.304	63%
IIb (10-5 000 ihn/km2)	969.620	2.337.815	37%
IIIa (5-3 000 inh/km2)	1.032.731	2.670.418	70%
IIIb (5-3 000 inh/km2)	449.297	1.161.785	30%
IVa (3-1 000 inh/km2)	1.235.055	3.297.873	38%
IVb (3-1 000 inh/km2)	1.984.415	5.298.836	62%
Va (1000 – 500 inh/km2)	379.034	1.051.714	21%
Vb (1000 – 500 inh/km2)	1.428.832	3.964.619	79%
VIa (500 – 100 inh/km2)	1.232.210	3.500.065	31%
VIb (500 – 100 inh/km2)	2.755.461	7.826.826	69%
VIIa (100 – 50 inh/km2)	741.787	1.997.873	56%
VIIb (100 – 50 inh/km2)	585.200	1.576.135	44%
VIIIa (50 – 10 inh/km2)	790.356	1.916.242	43%
VIIIb (50 – 10 inh/km2)	1.027.066	2.490.152	57%
IX (10 – 5 inh/km2)	323.441	668.735	100 %
X (<5 inh/km2)	168.155	317.055	100 %
Total	**17.950.398**	**46.745.807**	

BROADBAND IN SPAIN ADDITIONAL DATA

Table Annex 0.5 – Compilation of data on evolution of fixed lines in the Spanish market (CMT Annual Reports)

	2004	***2005***	***2006***	***2007***	***2008***	***2009***	***2010***	***2011***
Total number of lines	5.253.119	6.234.321	7.530.693	8.591.635	9.476.222	9.988.709	10.774.356	11.224.535
Switched lines	1.851.708	1.199.118	840.661	535.855	340.263	189.223	124.724	59.569
Broadband lines	3.401.411	5.035.203	6.690.032	8.055.780	9.135.959	9.799.486	10.649.632	11.164.966
xDSL	2.545.318	3.847.551	5.218.812	6.310.373	7.207.725	7.747.809	8.416.581	8.719.372
HFC	835.760	1.169.666	1.435.855	1.675.400	1.839.928	1.939.099	2.056.426	2.149.159
LMDS	7.611	13.400	23.035	34.882	2.939	2.459	4.028	2.621
WIFI-WIMAX	7.033	530	6.490	30.449	78.816	90.339	109.876	113.849
FTTH	0	0	0	0	3.885	18.669	59.981	177.122
Others	5.689	4.056	5.840	4.676	2.666	1.111	2.740	2.843
Residential	2.523.542	3.743.674	5.165.176	6.314.673	7.258.584	7.890.544	8.646.514	9.068.925
xDSL	1.715.324	2.676.783	3.781.821	4.677.726	5.454.735	5.972.200	6.574.110	6.825.166
HFC	793.033	1.053.509	1.354.175	1.573.922	1.722.752	1.817.631	1.922.898	1.989.701
LMDS	4.260	9.893	20.469	32.112	1.176	569	933	671
WIFI-WIMAX	6.934	452	5.654	29.174	75.984	84.206	94.568	100.175
FTTH	0	0	0	0	2.255	15.229	52.326	151.782
Others	3.991	3.037	3.057	1.739	1.682	709	1.679	1.430
Business	877.869	1.291.529	1.524.856	1.741.107	1.877.375	1.908.942	2.003.118	2.096.041
xDSL	829.994	1.170.768	1.436.991	1.632.647	1.752.990	1.775.609	1.842.471	1.894.206
HFC	42.727	116.157	81.680	101.478	117.176	121.468	133.528	159.458
LMDS	3.351	3.507	2.566	2.770	1.763	1.890	3.095	1.950
WIFI-WIMAX	99	78	836	1.275	2.832	6.133	15.308	13.674
FTTH	0	0	0	0	1.630	3.440	7.655	25.340
Others	1.698	1.019	2.783	2.937	984	402	1.061	1.413

Table Annex 0.6 – Compilation of data on NGAN deployment status, ultra broadband adoption and forecasts as of 2010. Source: industry data

Country - Operator	*Technology*	*Availability in total number of households*	*Total number of subscribers*	*Growth y-y*	*Investment*	*Minimum Speed*	*Source*	*Data issued in:*
World	FTTx	-	63.000.000 (End 2009)	-	-	-	IDATE	Sep 2010
World	FTTH/B	-	41.000.000 (End 2009)	15%	-	-	IDATE	Sep 2010
World	FTTH/B	306.000.000 (End 2014) 50% Asia 18% W Europe	-	-	-	-	IDATE	Sep 2010
United States	FTTH	20.000.000 (Sep 2010)	6.500.000 (Sep 2010)	-	-	-	RVA Market Research	Sep 2010
United States – Verizon FiOS	FTTH	18.000.000 (Dec 2010)	-	185.000 (Internet) 168.000 (TV)	-	-	Verizon	Jun 2010
China – China Telecom	FTTH	24.000.000 (Dec 2010)	-	-	-	-	China Telecom	Abr 2010
Chile - Telefónica	FTTH	700.000 (Dec 2014)	-	-	2,5 B$	-	Telefónica	Sep 2010
Europe	FTTH/B		3.500.000 (End 2009)	-	-	-	IDATE	Sep 2010
France	FTTH – 23% DOCSIS – 77%	4.500.000 (Mar 2010)	330.000 (Mar 2010)	-	-	-	ART	Mar 2010
Germany - DT	VDSL	25 % (Jul 2010)	-	-	-	-	DT	Jul 2010
UK - BT	VDSL-FTTC	66% (2015)	-	-	-	-	BT	May 2010
Italy – Telecom Italia	FTTH	50 % (2018)	-	-	8,93 B$	100 Mbps	TeleGeography	Sep 2010
Italy – FastWeb Wind Vodafone	FTTH	15 largest cities (2015)	-	-	3,2 B$	-	TeleGeography	Sep 2010
Austria – Telekom Austria	VDSL	40% - 1.590.000 (Dec 2010) 2.000.000 (2013)	-	-	-	-	Telekom Austria	Aug 2010

Table Annex 0.7 – Summary of data on NGAN deployments. Source (FEDEA, 2010)

NGAN	*Initiative type*	*Technology*	*Coverage Zone*	*Up/down max speed (Mbps)*	*Households*	*Municipalities*	*Users*	*Comments*
In use (red)								
1- Asturcón	Public	FTTH	Asturias	100/20	41.521	26	7.322	4 Different operators: Adamo, Eurona, Nostracom y Telecable
2- R	Private	DOCSIS 3.0	A Coruña, Ferrol, Lugo, Ourense, Pontevedra, Santiago y Vigo	100/3	450.000			
3- Cablex	Private	FTTH	Badajoz (Urb. Cerro gordo)		2.750		500	
4- Telefónica	Private	VDSL/FTTH	Madrid, Barcelona, Zaragoza, Islas Canarias, Murcia, Málaga, Sevilla, Valladolid, País Vasco	25-30/1				19.766 lines
5- ONO	Private	DOCSIS 3.0	Madrid	50/3	2.500.000			
6- Orange	Private	FTTH	Madrid (El Retiro, Chamberí, Vicalvaro) Decemeber 2010, Madrid and Barcelona	50/50	6.600 (forecast for Dec.2010)			
7- Adamo	Private	FTTH	Some buildings in Barcelona	100/20	2600			
8- Guifi.net	Private	FTTH	Gurb (Catalunya)	n.a.	3-12 up to 24			8000 wireless connections
In prospect (green)								
1- Miguelturra	Public	FTTH	Miguelturra (Ciudad Real)					
2- Castellón	Public		Some public buildings in Castellón					
3- Viladecans	Public	FTTH		100/dna	2.750			
4- Xarxa Oberta	Public	FTTH	Catalunya	>100/dna	.	1st stage: 281 municipalities Complete deployment: 946 municipalities (end of 2013)		5.843 nodes. Private operator: Imagina-Axia
5- Telecable-SOFIEX	Public-private	FTTH	Extremadura (1st stage: Badajoz, Cáceres, Mérida and Plasencia)	100 (up to 1Gbps)		Complete Project: 37 municipalities		2013: Coverage of all municipalities above 100 inhabitants. Agents involved: Telecable (51%) and SOFIEX (owned by Extremadura government) (49%)
6- Menorca	Public	FTTH						
7- Broadband Plan 2010-2013	Public	FTTH	Galicia				1.000.000 inh. forecast	

Table Annex 0.8 – Main public initiatives for broadband development from the supply side (Ramos, Arcos, & Armuña, 2009)

Project	*Region*	*Public Administration Role*	*Schedule*	*Investment Plan*	*Comments*
Avilés Ciudad Digital	Avilés City	Direct Intervention as operator	2007-2008	7M€	The objective is to offer free Internet access over a WiFi Network, financed by publicity.
Málaga WiFi	Málaga City	Direct Intervention as operator	2006-2010	206.000€	Free Internet access provision inside public buildings. The initiative is supported by Spanish Government through its Plan Avanza.
Wifi Ciutadà	Barcelona City	Direct intervention as operator	Phase 1: Basic service 2009 Phase 2: Premium Service 2010	Phase 1: 1,75 M€ (Internet inside public buildings) and 95.000€ /year maintenance	The objective is to offer free Internet access over a WiFi Network in public places. The CMT has allowed Barcelona Council to offer this free service only for one year.
Valencia Provincia WiFi	Diputación Valencia	Direct Intervention as operator	2010-2016	14 M€	Deploying a WiFi network for all Municipalities in Valencia
1 Mbps free	Junta Andalucía	Direct intervention setting PPP	2009-2010	9 M€	The objective is to offer free Internet access to every citizen.
Ciudad WiFi	Santa Cruz de Tenerife City	Direct Intervention as operator in colaboration with a private operator	Pending	Not specified	Free WiFi Access based on FON service
Localret	Catalunya	Direct intervention as neutral operator.	2006- 2016	233 M€	Deployment of a fiber optic network connecting all municipalities.
Asturcon	Principado de Asturias	Direct Intervention as operator	2007-2011	43 M€	FTTH Access network for wholesale and retail services provision
Broadband Extension Plan	Comunidad Foral de Navarra	Direct Intervention as operator	Phase 1: 2004-2007 Phase 2: 2007-2014	Phase 1: 9,7 M€ Phase 2: not specified	WiMAX access network
Broadband Plan	Comunidad de Castilla y León	Indirect intervention through subsidies	2003-2007	35M€	Wireless access network based on LMDS, WiMAX and WiFi
National Broadband Extension Programme	Spanish Government	Indirect intervention through subsidies	2005-2008	Investment required: 280M€ Public subsidies: 31M€ Zero interest loans: 51M€	Broadband access provision in rural areas without commercial offers availability

ANNEX II - ENERGY AND ICTS INITIATIVES AND OTHER RELATED PROJECTS

- European Commission: Code of Conduct on Energy Consumption of Broadband Equipment (EC 2011).
- ETSI: TS 102 533: EE - Energy consumption in BB Telecom Network Equipment. (ETSI 2008)
- Verizon NEBS Compliance: Energy Efficiency Requirements for Telecommunications Equipment (Verizon 2009).
- GreenTouch^{TM} (http://www.greentouch.org/) GreenTouch is a consortium of leading Information and Communications Technology (ICT) industry, academic and non-governmental research experts dedicated to fundamentally transforming communications and data networks, including the Internet, and significantly reducing the carbon footprint of ICT devices, platforms and networks.
- COST Action IC0804 - Energy efficiency in large scale distributed systems (http://www.cost804.org/)
- Energy aware radio and network technologies (EARTH) FP7 project (https://www.ict-earth.eu/default.html)
- GSMA's Mobile Energy Efficiency (MEE) Benchmarking service (GSMA 2011)

ANNEX III – SUMMARY OF PREVIOUS WORK AND CONTRIBUTIONS FOR THIS PHD

- STAREBEI Research Programme Project
  "Energy Efficiency in Ultra-Broadband Next Generation Access Networks"
- **International Telecommunications Society (ITS) Conferences**
  - 2011, Budapest (PhD Seminar)
    "A Simplified Energy Consumption Model for Fibre-Based Next Generation Access Networks"
  - 2012, Wien
    "On the Economics of Energy Consumption in 4G Networks: The Case of Spain"
  - 2012, Bangkok
    "Economics and Forecast of Energy Consumption in NGN Networks: The Case of Spain"
- **32nd Annual International Symposium on Forecasting, (Boston, 2012)**
  - *"Energy Consumption Forecast In 4G Networks: The Case of Spain"*
- **Telematics and Informatics Journal**
  (http://dx.doi.org/10.1016/j.tele.2011.11.005)
  - *"A simplified energy consumption model for Fibre-based Next Generation Access Networks."* Telematics and Informatics 29(4): 375-386.
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