A societal metabolism approach to job creation and renewable energy transitions in Catalonia

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Abstract:

This paper examines the feasibility of renewable energy transition scenarios and employment requirements on a backdrop of the objectives as described by the energy and climate change plan in Catalonia (PECAC 2012-2020). The analysis uses the Multi-Scale Integrated Analysis of Societal and Ecosystem Metabolism (MuSIASEM) approach as a framework for bringing together information regarding the demographic change, allocation of working hours, as well as mapping energy flows metabolized through the different compartments of the socio-economic system. Results indicate that the implementation of the energy plan in Catalonia would result in an increase in the overall energy metabolic rate by 2020, meaning 10% more energy is to be consumed per hour available in society. We conclude that this increase is linked to the need for greater primary energy sources for a transition to renewable energy sources, as well as the need for increasing skilled jobs to perform these tasks in the energy sector. For the case of Catalonia, we conclude that this would correlate to a requirement between 8,000 and 23,000 new jobs that will imply a shifting in current metabolic patterns should such a transition take place.

Keywords: MuSIASEM; energy transitions; energy planning; Catalonia

1 INTRODUCTION

1.1 The complexity of a renewable energy transition

Energy has played a fundamental role in economic and social development. Energy availability is linked to major trends of growth, development, evolution, and in some cases, to the decline experienced by many forms of social organization (Tainter, 1990). Traditionally, economic growth has been measured by changes in the production of goods and services. These goods and services are physical manifestations of net energy once delivered to society (King and Hall, 2011). Based on this relationship, over the years, several studies have scrutinized the strong correlation between gross domestic product (GDP) and energy consumption of societies (Alcántara and Duarte, 2004; Chontanawat et al., 2006; Granger, 1969; Sims, 1972; Yu and Hwang, 1984).

On the other hand, institutions and analysts in the energy sector point at the depletion of the rate of return of fossil fuel extraction (Aleklett and Campbell, 2003; Heinberg, 2007), as a cause of decreasing energy return on investment rates (EROI) (Hall et al., 2009; Inman, 2013; Lambert et al., 2012). This means that a higher proportion of energy production is forwarded to obtaining energy itself because the easy-and-cheap sources have already been exploited, so there is less funding for societal activities other than generating energy itself (Hall et al., 2014).

The above points describe a model with a positive loop that feeds the need to use a greater amount of energy (Figure 1). In other words, a more economized society will consume more energy and in turn, this energy will be more difficult to obtain considering that, investment rates are becoming lower for almost all sources of primary energy production. This can then be translated to an external pressure on energy consumption patterns taking into consideration reducing overall EROI. Thereafter, one can question the overall development and growth patterns we wish to or are able to, based on these biophysical constraints, replicate for the future.

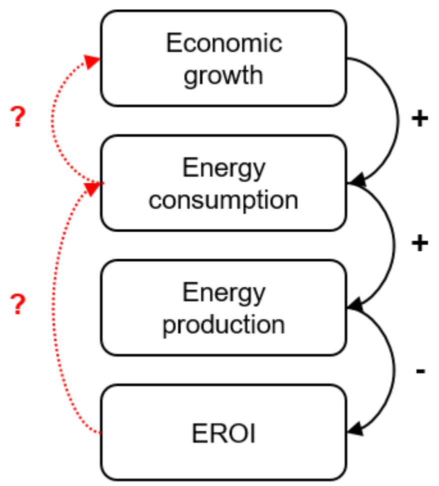

Figure 1. Causal loop diagram of energy consumption

Moreover, regarding climatic change, two-thirds of the emissions of generated greenhouse gasses (GHGs) are attributable to the energy sector (Mackay, 2009), a fact that suggests the importance of taking proper actions in order to stabilize the rate of current GHG emissions in this domain (Jiang et al., 2016; Zeng et al., 2016b). The environmental impacts caused by energy production increase the urgency of shifting the current energy model. Planning and establishing energy policies which guide us in transitioning to a more sustainable energy model (Folch et al., 2005; Maure and Baras, 2010). In general, energy plans have three strategic lines of action: (1) reduction of energy consumption (primary and final); (2) efficient distribution networks, which aims at reducing losses in energy transportation and delivery; and (3) implementation of renewable energy products and services. This paper focuses mainly along this last line of action: it aims at being an auxiliary tool in the decision-making process during the transition to renewable energies, considering the metabolism that societies portray and how these metabolic profiles will be modified based on this renewable energy transition.

In order to follow any of these lines of action, it is necessary to make a transition to renewable energies to stop relying on non-renewable fuels. However, the structural change of the primary energy sources (PES) of this transition will entail changes in the social structure that have not yet been analyzed holistically (Diaz-Maurin and Giampietro, 2013).

A transition based on renewable energy not only must reduce emissions, or reach a percentage share of the total energy consumed by society, but it also must ensure that desired societal functions can be executed through renewable modes of energy production. This transitional process must remain flexible to adapt to changing conditions under uncertain futures and functions of complex societal system (Smil, 2003). Therefore, energy transitions need to entail a long-term structural change in energy production systems, modes of consumption and accompanying a significant change in energy policies as well (Iychettira et al., 2017). The growth paradigm should be replaced with a new set of political and ethical pillars, which must eventually reach a “prosperous way down” (Odum and Odum, 2006).

Although it seems that a change in the energy sector structure is inevitable, we must ask ourselves whether societal conditions exist to achieve the objectives of energy plans. Among other variables, fundamental ones to take into consideration are:

- **Population structure**: The low fertility levels projected for Europe and the increase in life expectancy imply a process of population aging for this region. It is expected that demographic changes have a direct effect on economic growth, as a result of changes in the factors of production (Crespo Cuaresma et al., 2015). Changes in the workforce demographic structure will lead to changes in aggregate human capital in the form of experience and productivity (Kögel, 2005).
- **The standard of quality of life**: The quality of life depends on the possibilities that people have to adequately meet their basic human needs (Max-Neef, 1993). Although human needs are constant, the way they have been satisfied through time or among societies varies, depending on the energy availability (Smil, 2008). The basic goods and services that we require in modern civilization are highly dependent upon the delivery of net energy (Hall et al., 2009; Lambert et al., 2014).
- **The metabolisms of societies:** Diversity of activities carried out within the different compartments of society (Sorman and Giampietro, 2013). This refers to the structure of the productive sectors and the role they play in society, according to their hierarchy in the appropriation of flows, and occupation of funds.

The aim of this paper is to determine the feasibility of implementing renewable energy plans in the autonomous region of Catalonia (Spain) for 2020, with respect to the conditions and limitations established by the theory of urban metabolism (Georgescu-Roegen, 1971; Giampietro and Mayumi, 2000a, 2000b) and from comparative metabolic patterns (how and why we use resources), based on the forecast for supply - demand that is set in our case study.

Our analysis takes on from studying the objectives set out by the *Pla de l'Energia i Canvi Climàtic de Catalunya* (PECAC) 2012-2020 (en., Climate Change end Energy Plan for Catalonia, 2012 – 2020) and its scenario *Intensiu en Eficiència Energètica i Energies Renovables* (en., Intensive in Energy Efficiency and Renewable Energies (IER) (Institut Català d'Energia, 2012). This is done through the study of energy flows in Catalonia and considering its hypercycle and dissipative processes (Ulanowicz, 1986). The hypercycle processes produce all material goods used by a society (including energy). The hypercycle refers to the fact that this sector produces a surplus of material goods (Fix, 2015). In contrast, dissipative processes are only consuming ones, and they do not produce any material goods. The paper focuses on the relationship between human activity and energy consumed (within the hypercycle and dissipative processes), and aims at validating that objectives set out in PECAC 2012 - 2020 are the current patterns of energy consumption. For doing so, energy flows for the Catalan region are analyzed, starting with primary energy sources, with an emphasis on renewable energy. Consumption and losses related to generation and distribution of electrical energy and fuel are also included, as a previous step to reach final consumption in every productive sector. Complementarily, distribution profiles of human activity (hours available to perform each activity) within each productive sector are also included, as a means to describe social and cultural characteristics of the society under study.

2 METHODOLOGY

2.1 The Methodological Framework: Transitioning from Social Metabolism to Societal metabolism

The concept of social metabolism is used to describe the mode in which human societies organize their growing exchanges of energy and materials with the environment (Ayres, 1997; Fischer-Kowalski, 1998; Giampietro and Mayumi, 2000a; Haberl et al., 2011; Martinez-Alier, 1987). Social metabolism begins when societies appropriate the materials and energies of nature (input), and it ends when these are deposited as waste, fumes or residues in natural areas (output). Between these two steps, there occur other processes, where energy and materials are circulated, transformed and consumed (Toledo, 2013). Therefore, the process of social metabolism involves appropriation, transformation, and distribution of energy and materials into goods and services that are used by society in order to maintain different dissipative sectors (Figure 2). In this sense, energy metabolism describes how society uses energy inside the productive sectors for its continued operation.

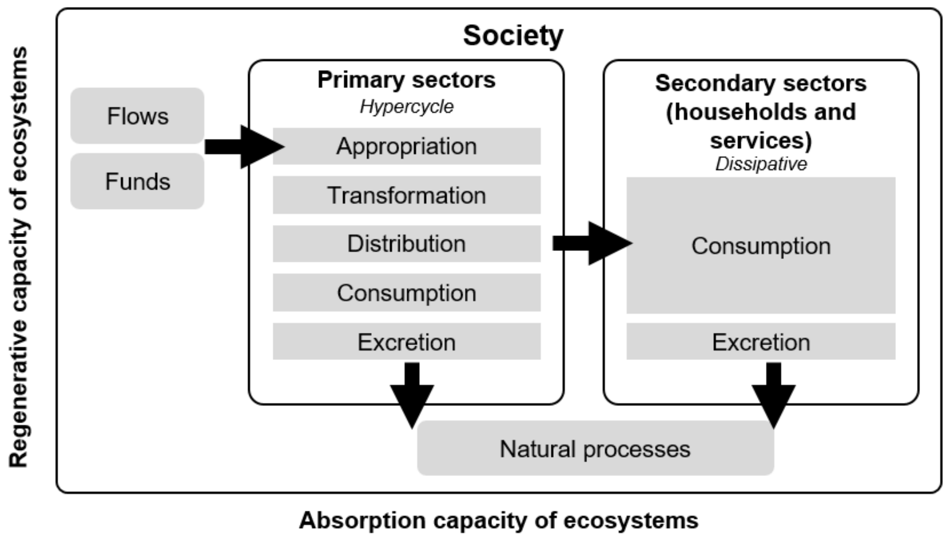

Figure 2. Structure of social metabolism. Adapted from (Giampietro and Pastore, 1998; González de Molina and Toledo, 2011)

According to Fischer-Kowalski (1998), the study of the socioeconomic metabolism along with the flow of materials can be a very useful tool in the interdisciplinary analysis of environmental performance indicators. This contributes to our understanding of the interrelationships between natural, social and economic processes, which are relevant for sustainable development (Fischer-Kowalski and Haberl, 2000).

On the other hand, societal metabolism puts its emphasis on the relationship between flows and the agents that transform input flows into output flows while maintaining and preserving their own identity (Sorman, 2014). Hence, it connects funds (i.e., the agents and transformers of a process) and flows (i.e., the elements that are utilized and dissipated) to generate indicators characterizing specific features of the system. Analyzing a complex system such as the energy sector using the methodology of societal metabolism can be an alternative providing an overview of the multiple streams involved in the system, allowing to understand the interactions and their effects on society.

The process of analyzing the metabolism of a specific society, that is identifying the characteristics of the exchange of material and energy with the environment, provides a framework to distinguish among different social forms of organization and cultures (Fischer-Kowalski and Haberl, 2000). Each society has a specific articulation across their metabolic processes, where social relationships are set up to encourage their reproduction and continuity. In order for social processes and environmental exchanges to be maintained over time, these processes should be embedded within boundaries set by the metabolism of ecosystems (Martinez-Alier, 1987).

2.2 The Multi-Scale Integrated Analysis of Societal and Ecosystem Metabolism (MuSIASEM)

In this paper, the analysis of societal metabolism is based on the Multi-Scale Integrated Analysis of Societal and Ecosystem Metabolism (hereafter referred to as MuSIASEM) tool introduced by (Giampietro and Mayumi, 2000a, 2000b, 1997) and thereafter developed by IASTE[1] and external partners. It is a method to characterize the metabolic patterns of systems and is used as a tool for decision support, thus allowing for different scenario analysis, including current trends and preferred scenarios to stay within the boundaries of the ecosystem. In addition, it is an open framework that takes into account the economic, environmental, social, cultural, technical and political dimensions in an integrated framework, and where different flows, such as monetary, energy, waste or water, can be integrated (IASTE, 2014).

This article focuses on the application of the MuSIASEM approach within the energy sector and the societal metabolism of the different sources of renewable energy in the conditions defined by the energy plans. However, we recognize the diversity of other multi-criteria approaches that allow us to compare inputs and outputs such as Three-DEA (Estelle et al., 2010; Li and Lin, 2016; Zeng et al., 2016a); Integrated Assessment Models (IAM), capable of assessing the feasibility of biophysical limitations such as IMAGE (Stehfest et al., 2014), ReMIND (Luderer et al., 2011), or EPPA (Wilkerson et al., 2015); which can provide a complementary view of the case study.

MuSIASEM aims at assessing the feasibility of energy budgets of societies, by checking the possibility of matching the demand and supply of energy flow through hierarchical levels of the different productive sectors. These flows are determined by technological

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aspects, the socio-economic identity, and biophysical conditions from each society (Sorman and Giampietro, 2013). The balance between energy supply and demand can be understood as the relationship among the parameters that determine the supply and demand itself (Giampietro & Pastore, 1998), and can be expressed as follows:

Energy demand = energy consumed per capita · population

Energy supply = (return on average energy of labor · work offer) in primary sectors

In this case presented here, the methodology is adapted to focus on the interlinkage and the relationship between human activity (HA) and the energy throughput (ET) by a society (table 1). The distribution of time (measured in hours) for each sector of the socioeconomic system represents and assess the size of these sectors, and it provides a direct and dynamic link to demographic and social parameters that should be reflected when defining energy plans within a society including (Giampietro and Mayumi, 2000b):

- Age-sex structure of the population.
- Rules and characteristics of the society with respect to age retirement.
- Duration of compulsory education.
- Existing access to higher education.
- Participation of women in the economic process.
- Legislation on working hours per week.

Table 1. Main variables of MuSIASEM. Source: (Ramos-Martin and Cañellas-Bolta, 2008)

Acronym	Name of the variable	Description	Unit	How is calculate?
TET	Total Energy Throughput	Total primary energy used in an economy in one year	Joule [J]	Statistical source
THA	Total Human Activity	Total human time a society has available for conducting different activities	Hour [h]	Population * 8760 h per year

Meanwhile, total energy consumption is expressed in primary energy sources (PES) measured in Joules. Energy losses, including generation and distribution, are associated with energy production (Giampietro et al., 2012). MuSIASEM considers the conversion of primary energy sources to final consumption, enabling the traceability of required energy.

The relationship between these variables reveals, an intensive variable, the metabolic pattern, relating flow elements (energy in Joules) to fund elements, (human activity in hours) (Table 2).

Table 2. Energy indicator of MuSIASEM. Source: (Ramos-Martin and Cañellas-Bolta, 2008)

Indicator	Definition	Unit	Formula	What does it measure?
EMR_{SA}	Metabolic pattern in society	MJ/h	= TET / THA	Energy consumed by hour available in society
EMR_i	Metabolic pattern in a specific sector	MJ/h	$= ET_i / HA_i$	Energy consumed per working hour in sector i

MuSIASEM describes the distribution of time and energy consumption for different hierarchical levels, which are defined from the different productive sectors within society, and for this case study to the different primary energy sources. (Figure 3). Energetic metabolic rate (or energy metabolic pattern) is defined as the relationship between energy consumption and available time in society for each productive sector. In other words, it describes how much energy is consumed per hour of human activity in each of the productive and non-productive sectors. [The Energetic Metabolic Rates in latter sections are further detailed based on fuel type used per hour of human activity].

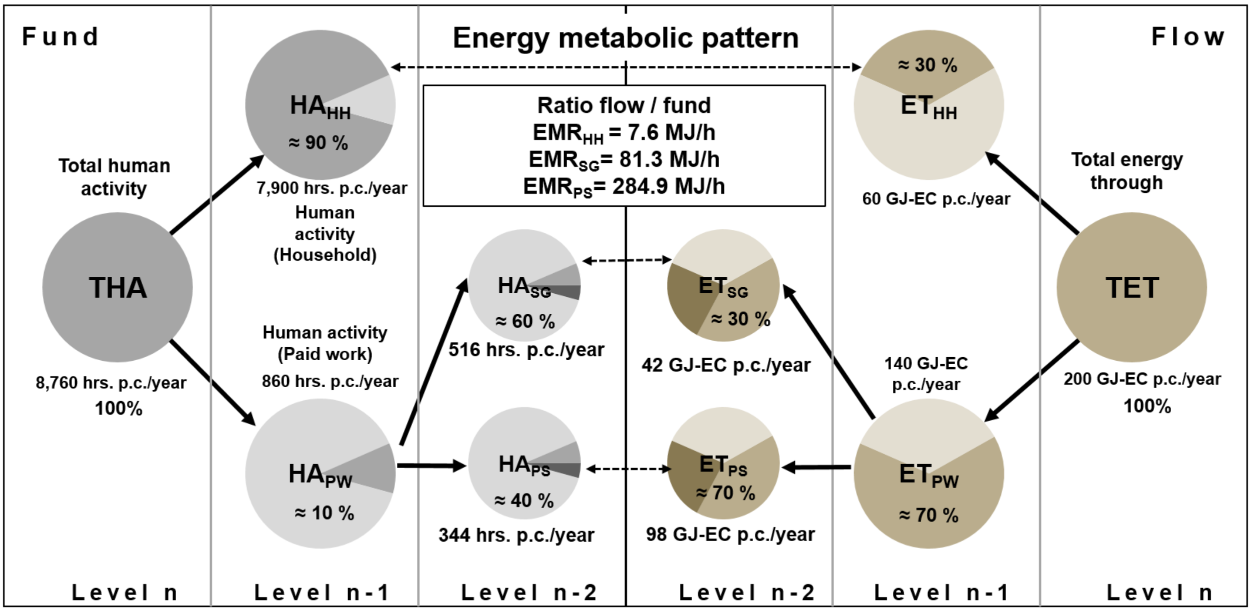

Figure 3. Example of calculation of energy metabolic pattern by level. Source: (Sorman and Giampietro, 2013)

The metabolic pattern allows analyzing the interactions among different sectors within a socio-economic system and its environment in which it is embedded (Kovacic and Giampietro, 2017). Furthermore, it allows making our societal system comparable to other societal systems (Ramos-Martin and Cañellas-Bolta, 2008). The per capita energy consumption of a society is strongly linked to lifestyles and productive models associated with them. In such way, societies in developed countries have similar metabolic patterns, and dissimilar from those existing in developing ones (Table 3).

Table 3. Benchmark of the metabolic pattern. Source: (Giampietro et al., 2012).

Benchmark values of metabolic patterns	Developed countries		Developing countries	
	EMR_i (MJ/h)	% THA	EMR_i (MJ/h)	% THA
SOCIETY	10-35	1	4-6	1
Households (HH)	2-10	0.93-0.9	0.5-1	approx. 0.9
Paid work (PW)	150-200	0.07-0.1	30-60	approx. 0.1
Services (SG)	80-100	0.05-0.06	10-20	approx. 0.05
Primary production (PS)	> 350	0.02-0.05	80-100	approx. 0.05

Once the variables are quantified for all defined levels, two accounting systems are applied for individual energy terms:

1. **Final consumption**. It is accounted to check the viability of the whole society functions required for its subsistence. It includes energy used in dissipative sectors.
2. **Primary energy sources** (PES). It allows comparing the needs for each primary energy source within the biophysical constraints of the environment (i.e., resource availability and hours of work available in the energy sector).

3 CASE STUDY

3.1 Study area

In this paper, we consider the autonomous region of Catalonia as the main level of the nested hierarchical scheme of MuSIASEM. Spain is included at the higher level (n + 1), although is not contained within the analysis. In the first sublevel (n - 1), socio-economic activity is divided into two groups (Figure 4):

- paid work (PW), responsible for the generation of added value,
- and households (HH), which refers to the activities that do not produce remuneration (i.e., time when the population is not working).

Both sectors consume energy for their maintenance and development, but PW is also responsible for ensuring a continuous supply of primary energy to the whole society (Ramos-Martín et al., 2009). In turn, PW is divided in two main subsectors within the level (n-2) according to the Catalan Classification of Economic Activities (CCAE-2009) (see supplementary information, table 1):

- Productive Sector (PS). These are sectors which produce any type of product, and they include in the next level (n-3): agriculture, livestock, fisheries and forestry (AG), industry (IN), including manufacturing and construction, and finally, energy and mining sectors (ES), which includes extractive industries and supply of electricity and gas; this is also referred to as the hypercycle as previously defined in section 1.1
- Service and Public administration Sector (SG), which includes in the next level (n-3): transportation (TR) and other services (SE). This level together with households sector, form the dissipative processes defined in section 1.1

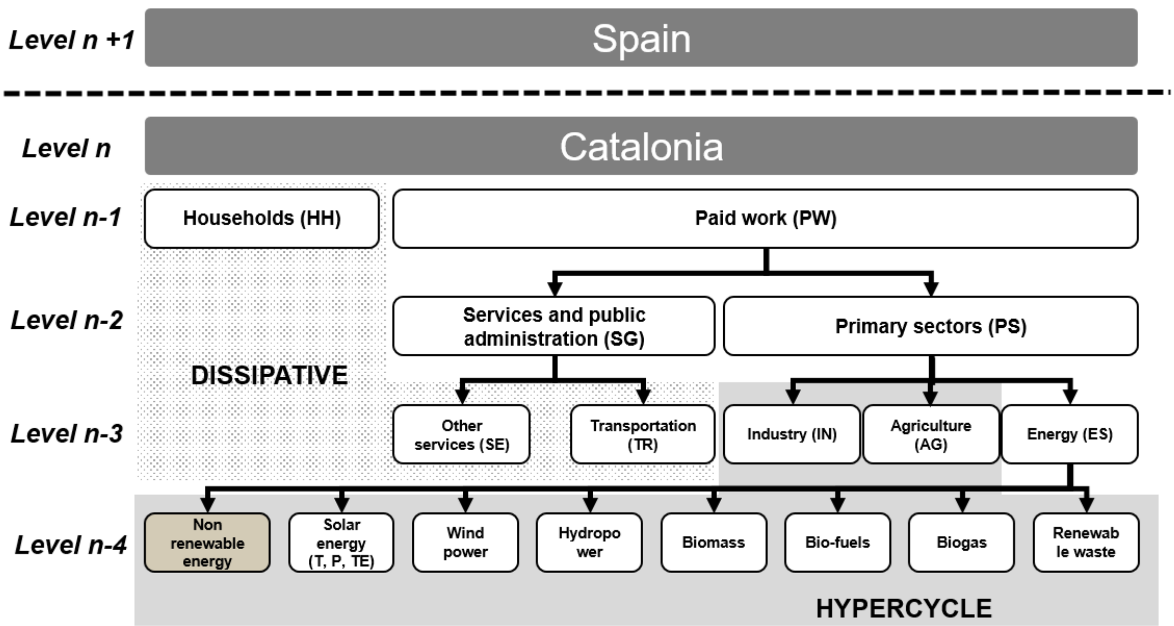

Figure 4. Hierarchies of complex socio-economic systems. Based on: (Giampietro and Mayumi, 2000a)

Finally, the last level (n-4) is divided by different methods of energy production, emphasizing the different sources of renewable energy. These sources are classified according to the provisions of the PECAC 2012-2020:

1. Solar energy (thermal, thermal and photovoltaic).
2. Wind Power.
3. Hydropower.
4. Energy forest and agricultural biomass.
5. Biogas and other biofuels.
6. Other renewable waste.
7. Conventional energy sources.

3.2 Demographic Data

The autonomous region of Catalonia is located in the northeast of Spain, bordering France, and it is known for its industrial and tourism sectors. Its population in 2013, represents around 16% of the total population in Spain. It is the first economy of the country in terms of Gross Domestic Product (GDP), producing 19% of Spain's GDP. Catalonia represents as well a large portion of primary energy consumption in Spain, with 21% in 2013 (Institut d'Estadística de Catalunya, 2013).

By 2020 Catalonia is expected to remain a leader in the Spanish economy, recovering a steady 2.2% per year in potential economic output (Correa-López and Mingorance-Arnáiz, 2012). The *Institut d'Estadística de Catalunya* (IDESCAT) has projected different scenarios for the demographic evolution of Catalonia for the coming years (Institut d'Estadística de Catalunya, 2014a) (Figure 5). The low scenario assumes a population degrowth which, by 2020 forecasts a decrease in a population of 7 million. This trend will continue for 2050, where the population will be reduced to 6.2 million. Meanwhile, the medium scenario does not expect a significant population growth in the next 10 years, and by 2050, the population is estimated to reach almost 8 million people. Finally, the high scenario assumes an exponential increase in population for the next 35 years, reaching 7.6 million by 2020 and more than 9.5 million people for 2050. The mid scenario will be considered for the estimates during our analysis as it shows an intermediate value of the expected 7 to 7.6 million by 2020.

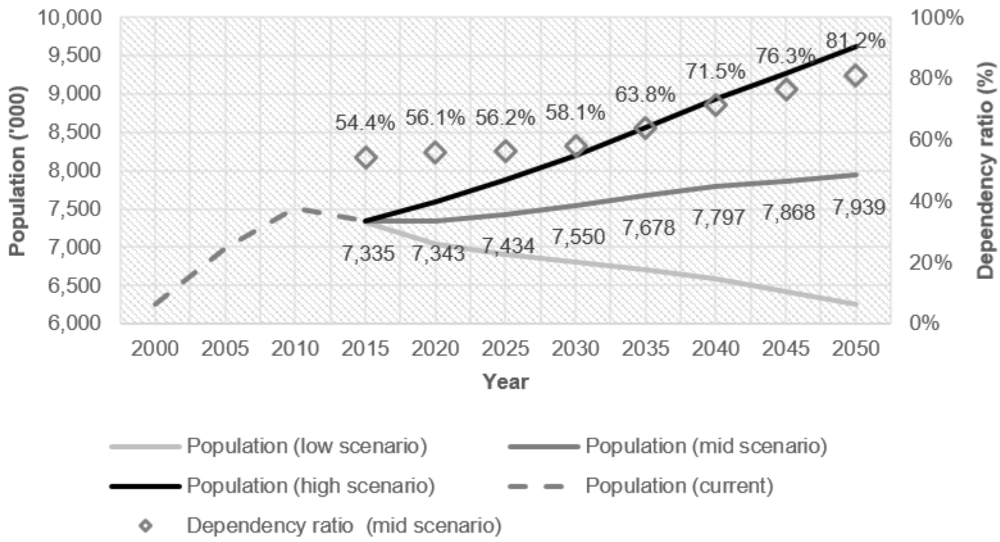

Figure 5. Population projections and dependency ratio in Catalonia (Institut d'Estadística de Catalunya, 2014a).

As many European regions, the population in Catalonia is aging, resulting in an increase in the dependency ratio (defined as the ratio between population aged under 15 and over 65, and population aged 16 to 64 years). It is projected to rise from 54.4% to 56.1% in 2020 and to 81.2% by 2050 (Figure 5). This is interpreted as a remarkable reduction in economically active people, who will burden the productive operation of the system with less working hours available to produce goods and services for a society with growing consumption habits.

In order to calculate the hours worked for each production sector (HA_i), we assume a total of 46 weeks of effective working time per year. The average worked hours in each age group and gender (Figure 6) is multiplied by the population in each group and productive sector (Figure 7). In 2011, 41% of the population was active in the productive sectors, with the services sector being the largest contributor to the occupation of Catalonia. Moreover, about 30% of the active population (between 16 and 65 years) were unemployed (i.e., without permanent employment).

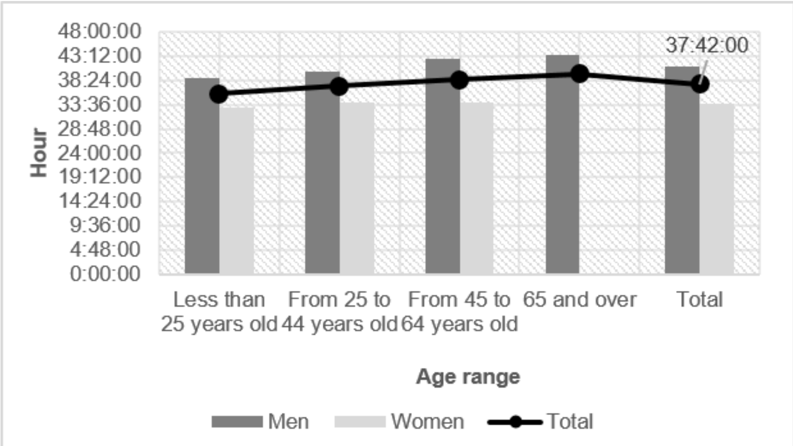

Figure 6. Average weekly hours worked. Source: (Institut d'Estadística de Catalunya, 2011a)

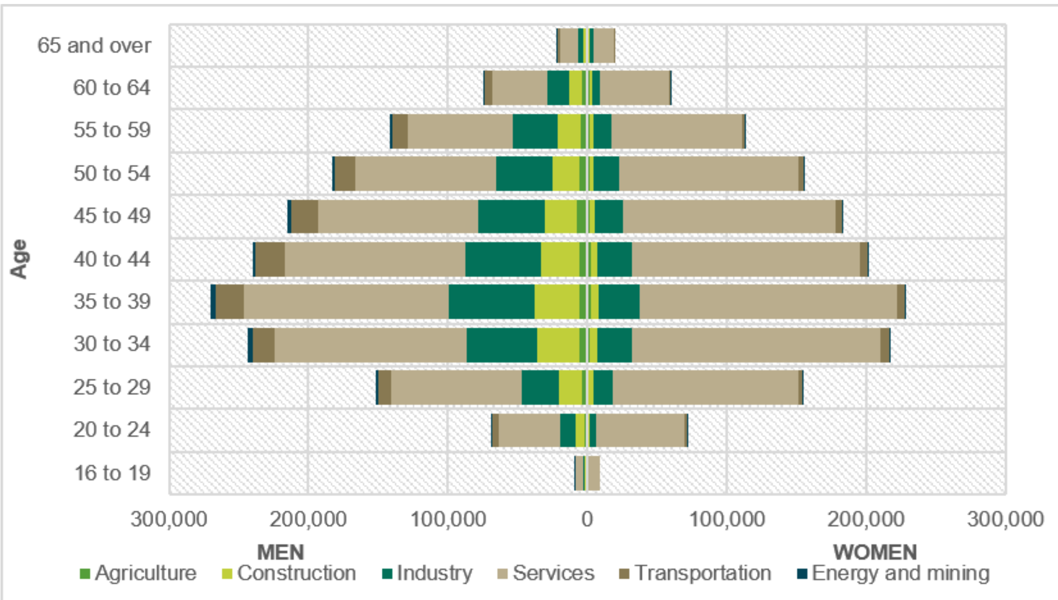

Figure 7. Population employed in Catalonia by productive sector, gender and age range in 2011. Source: (Institut d'Estadística de Catalunya, 2011b)

For the forecast of the employed population in 2020, we began with the average projection of the active population made by IDESCAT (Institut d'Estadística de Catalunya, 2011c), which is adjusted by the estimated percentage of the population that have a job (i.e., occupied population). In this case, 80%[2] of the working population is employed in different productive sectors. The labor participation of each sector is calculated according to the percentage share of each age group in each Catalan *comarca* (i.e., an administrative division similar to a shire). This geographical segregation is important because it allows including the socioeconomic characteristics of separate regions, such as agricultural, industrial or service areas as well as distinguishing different spatial demographic patterns.

3.3 Employment in the renewable energy sector and projections in Catalonia

Developed economies, in general, are facing economic stagnation accompanied by high and rising unemployment rates, particularly among young people. Youth unemployment rates in Europe reached 23.5% in the first quarter of 2013, more than twice the rate for the overall population (Meyer and Wolfgang Sommer, 2014). Renewable energy (RE) not only represents a solution to dependence on fossil fuels and climate change, it is also a trigger that encourages the creation of direct and indirect employment. In the case of Spain, the employment generated in renewable energy focuses mainly on the manufacturing, installation and, in a second term, operation and maintenance of renewable energy facilities (IDAE-ISTAS, 2011). According to reports made by Sustainlabour & OIT (2012), in Spain and during 2012, there were 148,394 jobs related

[2] Ratio between employed population and labor force reported by IDESCAT in 2014 (Institut d'Estadística de Catalunya, 2014b, 2014c).

to renewable energy, including 88,209 direct and 60,185 indirect jobs (labor activities that support those processes). Likewise, if renewable energy share of 20% of PES were reached in 2020, the sector would reach 124,265 direct jobs. RE jobs in Spain are segregate into wind power (37%), photovoltaic (19%) and biomass (17%). The relationship between the average number of jobs per unit of primary energy consumed (TJ) by type of renewable energy offers a first relationship between human activity and energy consumed in the renewable energy sector. However, as noted in table 4, the ratios of each renewable energy are very different, not only by source but by region, making it useful to study them separately.

Table 4. Distribution of employment by renewable energy. Sources: 1 (CCOO, 2009). 2 Estimate based on the ratio of direct employment - Indirect nationwide. 3 (Institut Català d'Energia, 2012). 4 (IDAE, 2011a). 5 (Sustainlabour and OIT, 2012).

	CATALONIA					**SPAIN**	
	Total direct employment 2008 [1]	**Total indirect employment 2008** [2]	**Total employment 2008**	**% share for renewable energy jobs**	**Ratio Total employment / PES (TJ)** [3]	**% share for renewable energy jobs**[4]	**Ratio Total employment / PES (TJ)** [5]
Wind power	1,204	963	2,167	22%	659	37%	310
Hydropower	111	50	161	2%	10	1%	21
Solar thermal	2,250	1,013	3,263	33%	4,235	7%	1,064
Solar thermoelectric	29	17	46	0%	-	10%	241
Solar photovoltaic	1,668	751	2,419	24%	2,397	19%	960
Biomass	202	194	396	4%	47	17%	122
Biofuels	192	197	389	4%	105	1%	22
Biogas	29	30	59	1%	31	1%	120
Others	221	97	318	3%	50	2%	348
Commons to all	430	274	704	7%	-	5%	-
TOTAL	**6,336**	**3,586**	**9,922**	**100%**	**239**	**100%**	**221**

At the Catalan level, a study about the employment in RE, elaborated by the Workers Commissions of Catalonia (CCOO, 2009), estimated around 10,000 jobs (6,336 of them in direct form) related to renewable energies (Table 4), with solar energy (thermal and photovoltaic) accounting for more than half of the total jobs. Wind energy represents an important source of renewable energy jobs, not only because it represents 20% of total jobs related to renewable energy, but it is expected a production growth for the coming years, according to energy plan for Catalonia (see Table 6, section 3.4).

Concerning employment, most of the reports in RE industries aim at assessing the number of existing jobs by means of analytical methods (Llera et al., 2013), considering usually only direct jobs (Wei et al., 2010). RE creates jobs geographically more dispersed because it depends on where the resource is located (González Vélez, 2009). It also has higher rates of employment per MW installed than conventional energy (International Renewable Energy Agency, 2011; Singh and Fehrs, 2001).

Recently in Spain, regarding RES, there has been a decrease in employment rate per MW of installed capacity, while installed power has been increasing at the same time (APPA, 2013) (Figure 8). This indicates stability and maturity of the sector of renewable energies[3], allowing it to absorb temporary jobs created during the installation (Llera Sastresa et al., 2010).

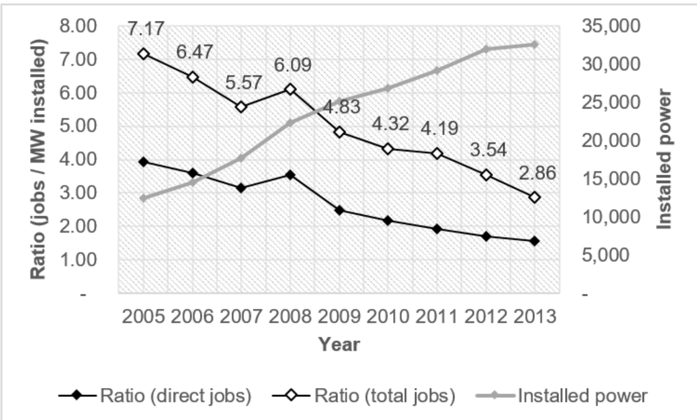

Figure 8. Variation of ratio and installed power in Spain from 2005 to 2013 (last year of available data). Data from (APPA, 2013).

[3] This relationship between jobs and installed power varies among each energy source (see supplementary information, figure 1), which emphasizes the importance of analyzing each technology separately, and to identify the date on which different data were obtained.

Therefore in an attempt to make a comprehensive review, we have considered six different data sources in relation to jobs related to renewable energies in Catalonia listed as follows:

1. **EU 1997 White Paper** (Commission, 1997). This White Paper describes the adoption of the policies, objectives, and lines of action, and it evaluates the costs and benefits of implementing renewable energies in Europe. It provides the energy contribution of renewable energies for the period 1995 - 2010, although it is possible to make a projection for values up to 2020. From this information, it is estimated a general rate of person-year per produced MW for RE, obtaining an average of one job for every 1,925 MWh/year (Martínez Magaña, 2004). This result, though general for all renewable energies, is the first approach to estimated number of jobs for each source.
2. **APPA** (APPA, 2013). This estimate is based on two different reports. Firstly, the study of the macroeconomic impact of renewable energies industry (APPA, 2013), which shows the number of jobs by RE for 2013 in Spain. Secondly, the Spanish Statistical Report on Renewable Energy IDAE (2014), which calculates the primary energy production for each source to the same period of time. With these two values, the rate of jobs per unit of primary energy by each source is obtained.
3. **CCOO** (CCOO, 2009). It considers the European Commission proposal to achieve 20% of end use from renewable energy and the replacement of 10% of the fuels used for transport by biofuels in 2020. This report includes the scenario "A", where a 2% annual increase of the energy demand is expected. The number of jobs is calculated in proportion to the percentage of installed capacity in Catalonia with respect to PECAC 2012 - 2020, except for the number of jobs in mini-hydro, which are considered as the values of the IDAE (see below), because PECAC does not

differentiate between hydraulic and mini-hydraulic energy. This report does not consider the jobs that come from waste incineration.

4. **IDAE** (IDAE-ISTAS, 2011). This report uses quantitative methods (survey companies) and installed capacity of each technology at the end of 2009. It segregates employment in the energy sector in two categories: (1) construction and installation (C&I) and (2) operation and maintenance (O&M), with different growth patterns. The first is associated with power installed each year, while the accumulated power is associated with O&M. The value of C&I is calculated from the difference between power installed in 2015 and the values are shown in the energy plan to 2020, assuming that energy facilities will be commissioned at the same rate over the next five years, 2015 – 2020. O&M is estimated from the accumulated power up until the end of 2020.
5. **RIOT-SAFIRE model** (ECOTEC, IDAE, & ESD, 1998). Funded by the European Commission under the Altener II program, this model assesses the impact on employment of the different renewable energy technologies. This study provides some employment indicators, expressed in full-time jobs (FTE, from 30 h/week), separated into two types of activity: employment in the manufacturing and installation of the equipment (M&I), expressed in jobs per million Euros invested (FTE / MEURO), and jobs created in the operation and maintenance (O&M) of equipment.
6. **ICAEN** (Institut Català d'Energia, 2012). The results are based on the provision of jobs created in Spain by renewable energies by 2020. This approach defines a ratio between occupation and installed power with national data. It is extrapolated to the expected power in the IER scenario of PECAC.

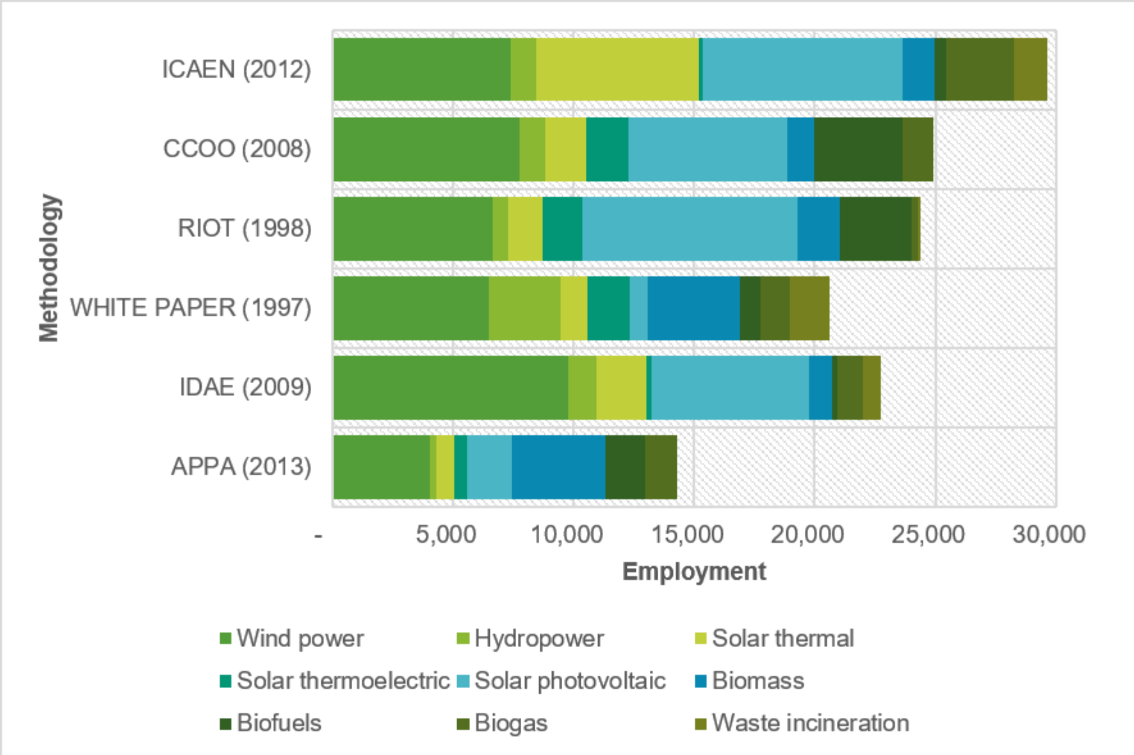

Figure 9. Forecasting of direct jobs in Catalonia for typology of renewable energy (2020).

Comparison benchmarks of other regions or coefficients have not been used due to the specific characteristics in terms of demographics, employment and RES type installation in Catalonia. These attributes instead have been highlighted with the MuSIASEM methodology that differentiates among the following:

- Application of different ratios considering different variables, such as installed power, power generation, and investment amount for the installation of different renewable energy technologies.
- These ratios used were obtained in different years and regions, increasing their variability.
- Finally, in some cases, where the information is incomplete, it was necessary to consider parameters from different references.

Considering the methodologies described, to our understanding, the IDAE-ISTAS methodology appeals the most to the current conditions in Catalonia. On the one hand, construction and installation are been separated from operation and maintenance, implying different growth rates of additional employment. In addition, the applied ratios were estimated from a sample closer to the study region, and in a period when employment growth has stabilized.

Hence, the average of employment by type of renewable energy will be defined to calculate metabolic rates with MuSIASEM methodology and assuming the scenario for 2020 with 22,702 jobs, which would mean an increase of 16,000 direct jobs in the next five years. These estimates do not include indirect employment, to avoid double accounting in some other productive sectors. However, if we consider that in the latest data in Catalonia these jobs represent about 50% of direct jobs (Table 4), it would be possible to include about 8,000 indirect jobs in Catalonia related to the different renewable energy technologies.

Although the previous methodologies do not mention the effects on jobs in conventional energies, Llera Sastresa et al. (2010) describes a stagnation in employment in the conventional energy sector in Spain in recent years, with a trend inversely proportional to employment growth in the renewable energy sector.

In the case of Catalonia, although it seems that renewable energy is not a perfect substitute for existing energy, it replaces the potential growth of conventional energies. In such cases, there is no substitution of jobs among energy technologies (Pfaffenberger et al., 2006). While the installed power of conventional energies has declined 4% in the last five years (mainly coal and cogeneration plants); the installed capacity of renewable energies has increased by 16% (Instituto Catalán de Energía, 2016).

3.4 Energy Data

In relation to production, distribution and energy consumption, Catalonia can be assimilated to the rest of Spain or the European Union, with greater participation in nuclear energy (20%) and only a share of 4.1% in renewable energies by 2009. Final consumption is distributed among the productive sectors similarly as the rest of Europe. The Catalan per capita consumption (138,164 MJ/c) behaves in the same way as the European average (137,745 MJ/c), being slightly above the Spanish one (Table 5).

Table 5. Comparative of energy Indicators for 2009. Includes no energy use. Sources: 1. (Institut Català d'Energia, 2012) 2. (International Energy Agency, 2014)

Energy data | year: 2009	**Catalonia [1]**	**Spain [2]**	**UE-28[2]**
Primary energy production (PJ)	250	1,253	34,325
Primary energy consumption (PJ)	1,017	5,461	69,314
Coal (%)	0.6%	7.9%	16.2%
Oil (%)	47.2%	46.3%	34.7%
Natural gas (%)	24.6%	23.9%	25.1%
Nuclear energy (%)	20.1%	10.5%	14.1%
Renewable energies (%)	4.1%	9.9%	9.7%
Balance of power exchanges (imp. - exp.) (%)	3.2%	-0.5%	0.1%
Final consumption (PJ)	609	3,807	48,173
Industry (%)	26.9%	24.2%	24.0%
Transportation (%)	41.0%	43.2%	33.0%
Households and others (%)	32.1%	32.6%	43.0%
Energy consumption per capita (MJ per cap)	138,164	115,555	137,745

The Pla de l'Energia i Canvi Climàtic de Catalunya (PECAC) 2012-2020, it is the document by the Institut Català d'Energia (ICAEN) which includes the concern about climate change, highlights the importance of energy in society, presents the application of different actions aimed at fulfilling the objectives of 2020 about energy efficiency, and promotes renewable energy as an alternative. Table 6 summarizes the objectives set for

2020 for primary energy consumption for each source of renewable energy sources (RES) in the IER scenario.

Table 6. Comparative of primary energy consumption 2010 – 2020. Source: (Institut Català d'Energia, 2012)

	Primary energy consumption			**Percentage of total**		
	Real data (PJ)		**PECAC 2020**	**Real data (%)**		**PECAC 2020**
Primary energy sources	**2008**	**2009**	**2020**	**2008**	**2009**	**2020**
Non-renewable energy	**1,035.7**	**975.7**	**929.3**	**96.9%**	**95.9%**	**85.4%**
Coal	9.3	5.7	1.4	0.9%	0.6%	0.1%
Oil	487.2	480.3	446.5	45.6%	47.2%	41.0%
Natural gas	273.1	249.8	225.6	25.5%	24.6%	20.7%
Nuclear	237.5	204.6	255.5	22.2%	20.1%	23.5%
Balance of exchanges (imp. - exp.)	25.5	32.2	- 5.0	2.4%	3.2%	-0.5%
Non-renewable waste	3.1	3.0	5.3	0.3%	0.3%	0.5%
Renewable	**33.4**	**41.6**	**159.0**	**3.1%**	**4.1%**	**14.6%**
Thermal solar	0.6	0.8	7.5	0.1%	0.1%	0.7%
Photovoltaic solar	0.4	1.0	5.1	0.0%	0.1%	0.5%
Thermoelectric solar	-	-	12.2	0.0%	0.0%	1.1%
Wind power	2.8	3.3	45.0	0.3%	0.3%	4.1%
Hydropower	14.8	16.1	20.8	1.4%	1.6%	1.9%
Biomass	4.4	4.3	26.5	0.4%	0.4%	2.4%
Renewable waste	5.7	6.1	11.4	0.5%	0.6%	1.0%
Biogas	1.8	1.9	8.5	0.2%	0.2%	0.8%
Biofuels	2.9	8.1	22.1	0.3%	0.8%	2.0%
TOTAL	**1,069.1**	**1,017.3**	**1,088.3**	**100.0%**	**100.0%**	**100.0%**

The aim for 2020 is constrained by the current European and national legislative framework, which attempts to increase the share of renewable energy to 14% of total primary energy sources. This means an increase of 117 PJ by 2020, a growth of 282% of PES done during 2010. The most important energy resource to achieve this objective is wind power, accounting for 28.3% of RES in Catalonia and increasing 13 times in the coming years. Consumption of forest and agricultural biomass is expected to reach 16% of the total primary energy RES, while biofuels could represent up to 14%. Hydropower represents 13.1% of the total, with an increase of 30%, essentially constrained by geography and environmental flows of rivers. Although data from ICAEN do not consider energy losses of biofuels (bioethanol and biodiesel) and biomass in combustible conversion, these were added by estimations based on conversion factors (IDAE, 2011b).

Our case study, therefore, compares two different scenarios to analyze the behavior of society through the current data and projections obtained from the energy plans:

a. **Baseline scenario**. It is based on data from 2009 (energy) and 2011 (demographics). It considers a 4% of total annual production is generated from renewable and it shows the current and expected energy consumption and metabolic patterns in Catalonia. This first picture allows understanding the differences among dissipative sectors.
b. **PECAC 2020 scenario**. It is based on the Climate Change end Energy Plan for Catalonia 2012 – 2020, and its Intensive in Energy Efficiency and Renewable Energies scenario (IER) (Institut Català d'Energia, 2012). It considers the objectives of primary energy sources and final consumption per productive sector by 2020. It contemplates the mid scenario of demographic evolution (Figure 6) and it sets an labor activity of 80% of active population (Institut d'Estadística de Catalunya, 2014b, 2014c). It was not adjusted to the original planning of supply and demand based on the PECAC, although considering the trend of RES, some of the objectives will not be achieved. For example, by 2015, the overall objective of installed capacity (MW) of RE was fulfilled by 85% (wind power 70%, solar photovoltaic 80%, solar thermoelectric 47%, biogas, and biomass 82% and 9% respectively), or be overcome (Hydropower 100%, urban solid waste 104%) (Institut Català d'Energia, 2016).

For each scenario, energy supply and demand by the productive sector and primary energy sources respectively, including generation and distribution losses, are considered. Furthermore, energy consumption is segregated into combustible and electrical energy (see Supplementary Information, Tables 2 and 3). Results of energy consumption will be used to calculate metabolism patterns for each hierarchical level (EMR_i). For the classification of renewable energy consumption in the productive sectors, an energy distribution according to the share of gross electricity production from each of the sources is considered (see Supplementary Information, Tables 4 and 5).

In particular for generation from renewable sources, Red Electrica Española (REE, operator of the electricity system in Spain) has studies aimed at assessing the integration capacity based on two technical perspectives: Suitability and Safety (Red Eléctrica de España, 2016a). Taken these into account, REE guarantees the supply and assures the correct and fundamental assessment of the acceptability of access requests. For the case of Catalonia, an according to REE report on May 2016 (Red Eléctrica de España, 2016b) the connection capacities technically permissible of the transport network nodes are around 400 MW (short circuit capacity) for the case of wind maximization, and between 220 - 240 MW for the maximization of other renewable sources. In addition, it does not have nodes with potential limitations, far from being saturated in their maximum connection range.

4 RESULTS

4.1 Dissipative and hypercycle consumption

In the year 2009, Catalonia consumed around 32% of PES in generation and distribution (i.e., hypercycle + losses) (Table 7). If PECAC objectives are reached, this value will increase to 36% (excluding non-energy consumption). This increase is caused mainly by power generation losses. On the other hand, renewable energies have a higher own use than fossil fuels, which means that more energy is required to produce the same amount of energy. Catalonia spends 11% of its energy consumption in the household sector, while the remaining energy is segregated among transport (28%), services (8%), agriculture (2%) and industry (18%).

For PECAC 2020, the household sector consumption will be similar to the baseline scenario, however, paid work sectors expected to increase by 8% of total energy consumption. Despite efforts in the transport sector decreasing by 9%, these will not be sufficient compared to the 12% and 20% increase in energy use in the industrial and energy sector respectively.

Table 7. Energy consumption per MuSIASEM hierarchical level for different scenarios. Primary energy sources (PES) [C] Combustible [E] energy.

	Levels	Baseline scenario				PECAC-2020				
		PES (PJ) [C]	**PES (PJ) [E]**	**PES (PJ)**	**% Part.**	**PES (PJ) [C]**	**PES (PJ) [E]**	**PES (PJ)**	**% Part.**	**Percent change**
N	**SOCIETY**	522.5	376.6	899.1	100.0%	515.0	446.9	961.9	100.0%	6.98%
N1	HOUSEHOLDS (HH)	58.0	41.2	99.3	11.0%	50.1	48.9	99.0	10.3%	0.24%
N1	PAID WORK (PW)	464.4	335.4	799.8	89.0%	464.9	398.0	862.8	89.7%	7.88%
N2	Services (SG)	266.6	57.9	324.6	36.1%	242.2	64.4	306.6	31.9%	5.52%
N3	Transportation (TR)	246.1	3.4	249.5	27.8%	222.0	5.3	227.3	23.6%	8.91%
N3	Other services (SE)	20.5	54.6	75.1	8.3%	20.2	59.1	79.4	8.3%	5.73%
N2	Primary production (PS)	197.8	277.4	475.2	52.9%	222.7	333.5	556.2	57.8%	17.03%
N3	Agriculture (AG)	20.0	1.4	21.3	2.4%	21.8	1.4	23.3	2.4%	9.12%
N3	Industry (IN)	101.8	62.2	163.9	18.2%	112.2	72.3	184.5	19.2%	12.55%
N3	Energy (ES)	76.1	213.9	290.0	32.3%	88.6	259.8	348.4	36.2%	20.15%

4.2 Metabolic patterns of the socio-economic sectors

The metabolic pattern of Catalonia (Table 8) of the baseline scenario presents values that fit the profile of developed countries (Giampietro et al., 2012) (Table 3, section 2.2). According to forecasts of supply and demand of energy plan for 2020, combined with the average population projection, the metabolic pattern of Catalonia will increase by 9.6%. In other terms, more energy is to be consumed per available hour to the society. Focusing on the performance of the energy sector specifically, the metabolic pattern is expected to increase by 15%. It should be noted that here, Energetic Metabolic Rates have also been illustrated by type of fuel use (energy carrier) in terms of fuel [C] and electric power [E]. Each renewable energy type entails specific losses associated to conversion features of the specific technology. A mix of the renewables will demand a series of different conversion losses, especially for technologies like solar thermal energy, which has high losses in its conversion to electricity (IDAE, 2011a). RES also expect an increase in its energetic metabolic rate in terms of electricity due to the versatility and easiness in use and provision in all sectors.

Table 8. Comparison of changes in metabolic pattern between scenarios. [C] Combustible, [E] Electric power.

Levels		Baseline scenario			PECAC 2012-2020			Percent change		
		Met. rate (MJ/h)	**Met. rate [C] (MJ/h)**	**Met. rate [E] (MJ/h)**	**Met. rate (MJ/h)**	**Met. rate [C] (MJ/h)**	**Met. rate [E] (MJ/h)**	**Met. rate (MJ/h)**	**Met. rate [C] (MJ/h)**	**Met. rate [E] (MJ/h)**
N	SOCIETY	13.6	7.9	5.7	15.0	8.0	6.9	9.6%	0.9%	21.5%
N1	HOUSEHOLDS (HH)	1.6	1.0	0.7	1.7	0.9	0.8	3.1%	-10.7%	22.6%
N1	PAID WORK (PW)	151.7	88.1	63.6	151.2	81.4	69.7	-0.4%	-7.6%	9.6%
N2	Services (SG)	85.0	69.8	15.2	74.0	58.5	15.6	-12.9%	-16.3%	2.5%
N3	Transportation (TR)	883.5	871.6	12.0	745.4	728.0	17.4	-15.6%	-16.5%	44.9%
N3	Other services (SE)	21.2	5.8	15.4	20.7	5.3	15.4	-2.6%	-9.1%	-0.1%
N2	Primary production (PS)	327.1	136.2	191.0	355.1	142.1	212.9	8.5%	4.4%	11.5%
N3	Agriculture (AG)	187.0	175.0	12.0	167.6	157.3	10.3	-10.4%	-10.1%	-14.0%
N3	Industry (IN)	126.9	78.8	48.2	133.9	81.4	52.4	5.5%	3.3%	8.9%
N3	Energy (ES)	6,134	1,610	4,524	7,055	1,794	5,261	15.0%	11.5%	16.3%

As described in section 3.2, demographic data estimations vary significantly among scenarios. Based on the results of the metabolic pattern, and considering the expected energy consumption in the energy plan for 2020, it is possible to analyze the variation in energy consumption according to different scenarios of population growth (see Supplementary Information, Table 6). To develop energy consumption calculations, we assume: (a) a percentage of 80% of active and employed population, (b) employment in each sector according to the current share, taking into account gender and age range (i.e., groups of 16-24, 25-55 and 56-69 years), and (c) PES consumption for non-energy uses are not considered. According to the results, PES consumption stands between 880 PJ to 1051 PJ. This means that, while the population could vary by 8% between low and high scenario, PES consumption is more variable, because it can increase up to 19% among scenarios. In per-capita terms, the results are between 125 GJ and 138 GJ.

4.3 Renewable energy employment

According to our results, the metabolic pattern of the energy sector will increase by 15% over the next five years. However, each category in RES presents very different behaviors, where in some cases metabolic rates increase up to 10 times, especially for wind power and biomass (Table 9). Through using the MuSIASEM approach, it is pointed out that estimations of increased generation by RES in current energy plans, fail to consider an increase in the workforce required in the sector.

Table 9. Variation in metabolic rates for different Renewable Energies. N/D: Undetermined

Levels		Baseline scenario			PECAC 2012-2020			Percent change
		Met. rate (MJ/h)	Met. rate [C] (MJ/h)	Met. rate [E] (MJ/h)	Met. rate (MJ/h)	Met. rate [C] (MJ/h)	Met. rate [E] (MJ/h)	Met. rate (MJ/h)
N4	NON-RENEWABLE ENERGY	7,733	1,996	5,737	7,943	2,094	5,848	2.7%
N4	RENEWABLE ENERGY	844	331	512	4,121	802	3,319	388.5%
N4	Wind power	177	-	177	2,054	-	2,054	1059.4%
N4	Hydropower	9,378	-	9,378	10,291	-	10,291	9.7%
N4	Thermal solar	N/D	-	-	N/D	-	-	0.0%
N4	Solar thermoelectric	-	-	-	177,855	-	177,855	0.0%
N4	Photovoltaic solar	39	-	39	169	-	169	332.9%
N4	Biomass	3,092	3,066	26	44,520	7,084	37,436	1339.9%
N4	Biofuels	7,706	7,706	-	19,009	19,009	-	146.7%
N4	Biogas	19,483	-	19,483	54,337	-	54,337	178.9%
N4	Renewable waste	6,141	-	6,141	12,840	-	12,840	109.1%

According to the active population estimate made by IDESCAT 2020, and considering an equal ratio of employment in each productive sector, it is possible to reach about 27,000 jobs in the energy sector, including jobs in conventional energy production and renewable energy. It represents 6,600 jobs in renewable energy, when considering a similar proportion of jobs among both renewable and conventional energy. However, estimations of energy sector jobs presented previously (see section 3.3) show that in order for the 2012-2020 PECAC objectives to be fulfilled, the sector would need from 14,000 to 29,000 jobs created by the activity of the renewable energy sector. These new jobs dedicated to the energy sector are not considered in estimates of labor force by IDESCAT. This implies a shortage of dedicated people to fill these jobs by 2020, at least in theory. If the demographic and labor force projections had achieved, these jobs would have to be supplied from other productive sectors, which may occasionally reduce its production capacity by reducing their estimated working hours. On the other hand, jobs related to fossil fuels would be affected and would have to accompany the transition to renewable energy. This fact implies a need for 8,000 to 23,000 new jobs over the next five years if PECAC energy objectives are to be reached, which represents between 1% and 4% of the total unemployed population in Catalonia. This opens quite attractive possibilities for new professional profiles in Catalonia, which require specific knowledge and skills for the next generation of graduates.

One last important aspect we want to explore is the functional correlation between employment and metabolic rate, in order to detect their level of dependence. Using values of employment from our previously presented scenarios, Figure 10 shows the evolution of the metabolic rate as a function of the employment. We observe that this correlation follows a simple power law function $y \sim x^b$, with the scaling exponent $b = -1.164$ and adjusted $R^2 = 0.982$. Scaling behaviors appear as a very common statistical trait in many complex systems (Newman, 2005).

For example, in urban contexts, many properties of cities that characterize their inner dynamics at all levels (social, infrastructural, cultural, etc.) are shown to be power-law functions of population size (Bettencourt et al., 2007). In contrast with biological systems, where economies of scale associated with optimal and efficient behaviors are the usual outcome, observables of man-made systems like urban agglomerations present more variability. Whereas quantities involved in infrastructural variables also show material economies of scale with sublinear exponents (i.e., $b < 1$), those reflecting social interactions have superlinear (increasing returns) correlation with population size (i.e., b > 1). In our case study, a negative superlinear exponent such as b = -1.164 implies that as the employment in renewables grows, metabolic rate decreases more than the value that would have if this was strictly proportional to the increase in employed population.

Scenarios	Employment	Metabolic rate (MJ/h)
Baseline scenario	6,038	6,134
PECAC 2012-2020 scenario	6,600	4,121
Bottom employment (2020)	14,274	1,781
Top employment (2020)	29,651	857
Average employment (2020)	23,093	1,101

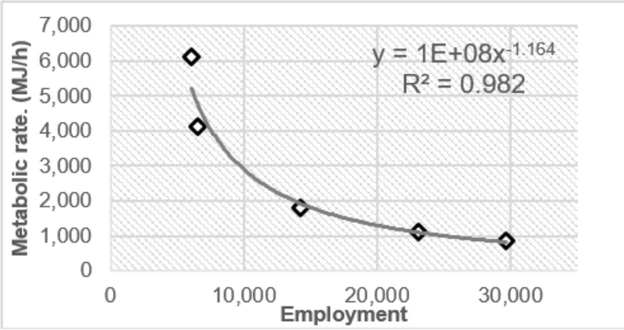

Figure 10. Relationship between employment of renewable energy and metabolic pattern.

5 DISCUSSION AND CONCLUSIONS

The conversion of primary energy sources in the flow of energy carriers to final consumption allows for traceability of necessary raw materials extracted as well as the losses generated during the production and distribution of energy. According to our results, and compared to the baseline scenario, the share of PES consumption in the energy sector is likely to increase. This means that a greater amount of primary energy will be needed in order to meet the energy needs of the Catalan society, although a lower final consumption per capita is expected.

The metabolic patterns of Catalonia depict a region with a developed socioeconomic structure as its ratios (current and forecast for the next years) fall within the range of those of developed countries. Yet, economic development involves drastic changes in the overall size and pattern of metabolism, and the structural typology of dynamic energy budget, forcing a reallocation of human activity profiles in various economic sectors. The results pose a problem along three main factors:

1. The demand for primary energy will likely grow the coming years (unless major changes in the economic system take place) despite efforts to reduce final consumption and increase the participation of renewable energies.
2. Likewise, the need for renewable energy is evident, which will further promote the increased primary energy source by having rates of own use higher than fossil fuels,
3. Finally, our society will continue to age, a fact that implies a growing dependence of the active population. Theoretically, this situation should promote a reduction of the unemployed population (4% in our case study). Otherwise, the working population will have to increase their productivity to fulfill the needs of dissipative sectors (which are growing), and thus to be able to maintain the structure of the modern Catalan society. An almost zero population growth together with a huge economic dependency ratio is a restriction on the biophysical conditions of the region and will determine and modify the structure of its societal metabolism, strongly reducing economic growth estimates.

These three points seem to have no compatibility with each other or with the model of perpetual economic growth. The need for greater weight in the production of energy from renewable sources will be linked definitely to a change in the current labor structure, involving a transition in the socio-economic to a new system. Hence, the metabolism of society itself has to change because it will not be able to continue to show the same pattern as before and have other completely new features.

An alternative to solve this problem would be to improve the efficiency of RES and achieve higher values of EROI. However, this scenario is improbable in the medium term technology currently available. Moreover, forecasts for the coming years continue to show to fossil fuels as the primary source, which also will decrease their energy performance through the years. Focus on improving energy efficiency can bring secondary problems as the Jevons Paradox[4], which occurs when technological advances increase the efficiency with which a resource is used, nonetheless also causes an increase in the rate of consumption, causing a higher demand than the original; efficiency and productivity increase economic growth, generating more jobs; but also stimulate higher energy consumption throughout society.

Finally, according to correlation between employment and metabolic rate, a continuing effort to promote green policies and to increase jobs in the renewables sector well over the PECAC 2012-2020 value would have a very noticeable non-linear effect on reducing the absolute metabolic rate of Catalonia. The integration of societal metabolism into energy policy actions and plans allows shedding light onto the socio-economic structure of the region, as well as to assessing the feasibility of planned objectives. With a higher employment rate for every MW generated by renewable energy, any energy plan will have to consider strategies to cover a larger share of employment in the energy sector. First, with a gradual transition from conventional energy jobs, and second, through the participation of other productive sectors. If we consider a decreasing or stable demographic trend, this will mean a reduction of hours available in other productive sectors, and therefore a modification to the actual metabolic pattern.

[4] The Jevons Paradox was introduced by William Stanley Jevons in 1865. He described a phenomenon in the coal sector. According to the paradox, the invention of more efficient equipment led to an overall higher consumption of coal, being more extraction that is profitable. (Polimeni, 2007).

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8 SUPPLEMENTARY INFORMATION

Table 1. Classification of Economic Activities

SECTOR	Classification (CCAE-2009)
AG	Agriculture, livestock, forestry and fisheries
ES	Extractive industries
IN	Manufacturing industries
ES	Supply of electricity, gas, steam and air conditioning
IN	Submit. Water; sewerage, waste management and remediation
IN	Construction
SE	Wholesale / retail; repair of motor vehicles and motorcycles
TR	Transportation and storage
SE	Hospitality
SE	Information and communication
SE	Financial and insurance
SE	Real estate activities
SE	Professional, scientific and technical
SE	Administrative and support service activities
SE	Public administration, defense and compulsory social security
SE	Education
SE	Human health and social services
SE	Arts, entertainment and recreation
SE	Other services
SE	Active households occupying pers. dome. or produce goods / services for own use
SE	Extraterritorial organisms

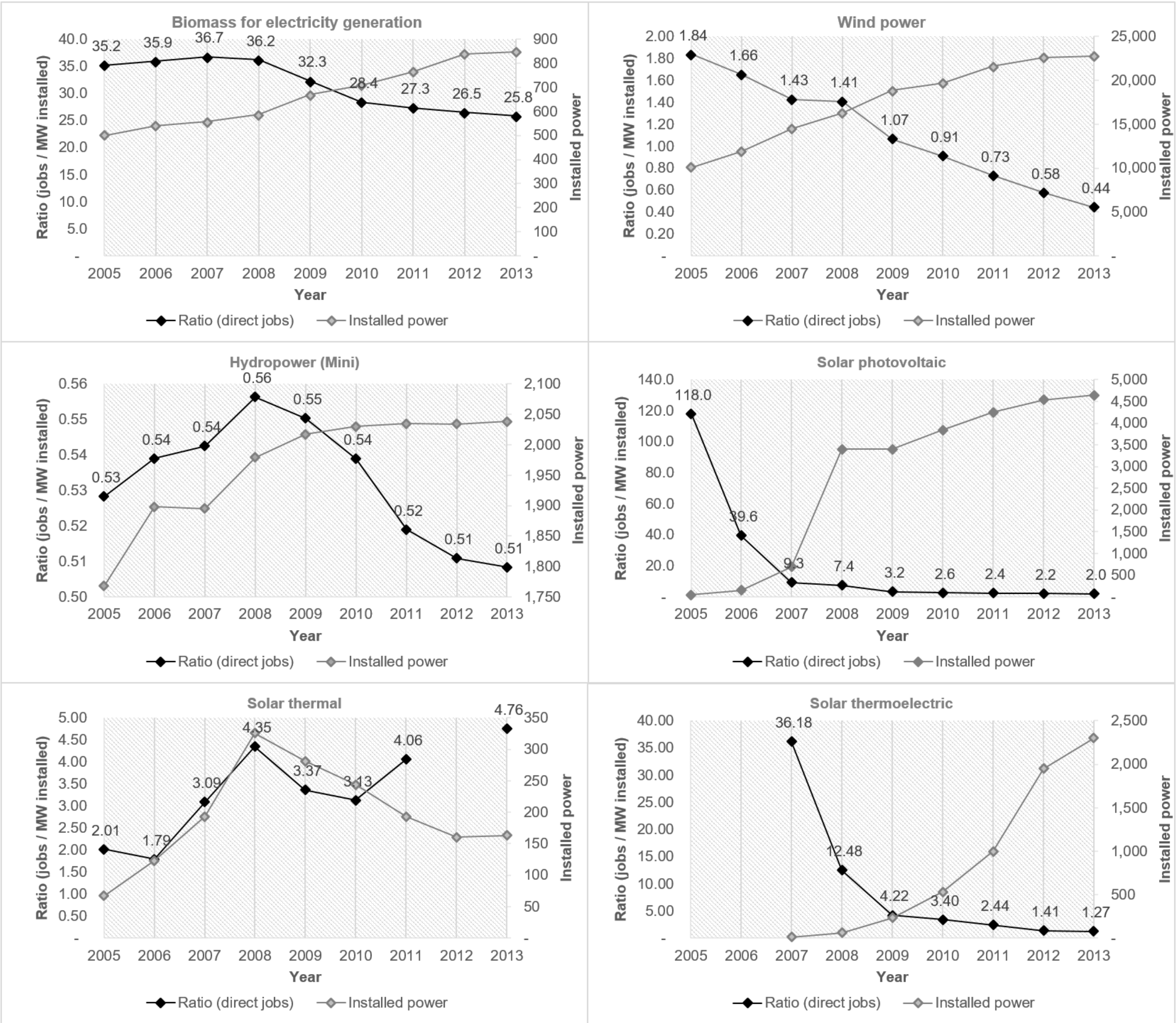

Figure 1. Variation of ratio and installed power in Spain for typology of renewable energy. Data from (APPA, 2013)

Table 2. Summary of supply – demand energy in Catalonia 2009.

Consume in PJ (2009)	**IN**	**HH**	**SE**	**AG**	**TR**	**Own use**	**Non-energetic**	**Transp. Losses**	**Power generation losses**	**TOTAL**
COMBUSTIBLE [C]	101.8	58.0	20.5	20.0	246.1	68.4	121.9	- 2.1	9.7	644.3
Coal	1.2	0.0	0.0	-	-	-	0.4	-	-	1.6
Fuels	25.8	12.0	5.8	19.3	237.5	57.0	121.3	-	6.0	484.8
Natural gas	70.3	43.4	13.9	0.6	0.5	11.4	0.2	- 2.1	0.1	138.4
Non-renewable waste	2.0	-	0.1	-	-	-	-	-	-	2.1
RENEWABLE ENERGY	2.5	2.5	0.7	0.1	8.1	-	-	-	3.6	17.5
Thermal solar	0.0	0.6	0.2	-	-	-	-	-	-	0.8
Biomass	1.9	2.0	0.4	0.1	-	-	-	-	1.1	5.4
Renewable waste	0.3	-	0.1	-	-	-	-	-	-	0.4
Biogas	0.2	-	0.1	-	-	-	-	-	-	0.3
Biofuels	-	-	-	-	8.1	-	-	-	2.6	10.7
Bioethanol	-	-	-	-	1.3	-	-	-	0.9	2.3
Biodiesel	-	-	-	-	6.8	-	-	-	1.6	8.4
ENERGY POWER [E]	62.2	41.2	54.6	1.4	3.4	8.4	-	12.2	193.3	376.6
Import - export balance	10.9	7.3	9.6	0.2	0.6	1.5	-	2.1	-	32.2
Coal	0.5	0.3	0.4	0.0	0.0	0.1	-	0.1	2.7	4.2
Fuels	0.2	0.1	0.2	0.0	0.0	0.0	-	0.0	1.3	1.9
Natural gas	19.6	13.0	17.2	0.4	1.1	2.6	-	3.8	47.3	105.1
Nuclear	23.1	15.3	20.3	0.5	1.3	3.1	-	4.5	136.4	204.6
Non-renewable waste	0.5	0.3	0.4	0.0	0.0	0.1	-	0.1	2.3	3.8
RENEWABLE ENERGY	7.3	4.9	6.4	0.2	0.4	1.0	-	1.4	3.2	24.8
Hydropower	5.4	3.6	4.8	0.1	0.3	0.7	-	1.1	0.0	16.1
Wind power	1.1	0.7	1.0	0.0	0.1	0.2	-	0.2	0.0	3.3
Photovoltaic solar	0.3	0.2	0.3	0.0	0.0	0.0	-	0.1	- 0.0	1.0
Thermoelectric solar	-	-	-	-	-	-	-	-	-	-
Biomass	0.0	0.0	0.0	0.0	0.0	0.0	-	0.0	0.0	0.0
Biogas	0.2	0.2	0.2	0.0	0.0	0.0	-	0.0	0.9	1.6
Renewable waste	0.2	0.1	0.2	0.0	0.0	0.0	-	0.0	2.3	2.9
TOTAL	**163.9**	**99.3**	**75.1**	**21.3**	**249.5**	**76.8**	**121.9**	**10.1**	**199.4**	**1,017.3**

Table 3. Summary of supply – demand energy in Catalonia for 2020 at IER Scenario

Energy consume (PJ) | PECAC-2020	IN	HH	SE	AG	TR	Own use	Non-energetic	Transp. Losses	Power generation losses	TOTAL
COMBUSTIBLE [C]	112.2	50.1	20.2	21.8	222.0	71.1	135.6	2.0	15.5	650.6
Coal	1.0	-	-	-	-	-	0.4	-	-	1.4
Fuels	20.3	6.2	3.7	19.7	199.0	58.8	135.3	-	6.1	449.1
Natural gas	73.3	36.7	12.5	0.4	0.8	12.3	-	2.0	0.2	138.2
Non-renewable waste	4.5	-	-	-	-	-	-	-	-	4.5
RENEWABLE ENERGY	13.1	7.2	4.1	1.7	22.1	-	-	-	9.2	57.4
Thermal solar	2.3	3.3	1.8	0.0	-	-	-	-	-	7.5
Biomass	4.5	3.9	1.6	0.4	-	-	-	-	2.6	12.9
Renewable waste	5.1	-	0.3	-	-	-	-	-	-	5.4
Biogas	1.2	-	0.4	1.3	-	-	-	-	-	2.8
Biofuels	-	-	-	-	22.1	-	-	-	6.6	28.7
Bioethanol	-	-	-	-	2.8	-	-	-	2.0	4.8
Biodiesel	-	-	-	-	19.3	-	-	-	4.6	23.9
ENERGY POWER [E]	72.3	48.9	59.1	1.4	5.3	8.8	-	12.3	238.6	446.9
Import - export balance	-	-	-	-	-	-	-	-	-	-
Coal	-	-	-	-	-	-	-	-	-	-
Fuels	0.4	0.3	0.4	0.0	0.0	0.1	-	0.1	1.0	2.2
Natural gas	15.3	10.3	12.5	0.3	1.1	1.9	-	2.6	36.0	80.0
Nuclear	29.0	19.7	23.8	0.6	2.1	3.5	-	5.0	168.7	252.3
Non-renewable waste	0.1	0.1	0.1	0.0	0.0	0.0	-	0.0	0.2	0.5
RENEWABLE ENERGY	27.4	18.6	22.4	0.5	2.0	3.3	-	4.7	29.9	108.9
Hydropower	6.9	4.7	5.7	0.1	0.5	0.8	-	1.2	0.0	20.0
Wind power	15.1	10.2	12.3	0.3	1.1	1.8	-	2.6	0.0	43.4
Photovoltaic solar	1.7	1.2	1.4	0.0	0.1	0.2	-	0.3	0.0	4.9
Thermoelectric solar	1.0	0.7	0.9	0.0	0.1	0.1	-	0.2	9.0	12.0
Biomass	1.3	0.8	1.0	0.0	0.1	0.2	-	0.2	13.3	16.9
Biogas	1.0	0.7	0.9	0.0	0.1	0.1	-	0.2	2.5	5.6
Renewable waste	0.4	0.3	0.3	0.0	0.0	0.0	-	0.1	5.0	6.1
TOTAL	**184.5**	**99.0**	**79.4**	**23.3**	**227.3**	**79.9**	**135.6**	**14.4**	**254.1**	**1,097.5**

Table 4. Generation of electricity by type of energy 2009. Source: (Institut Català d'Energia, 2012)

Electricity generation 2009 (PJ)	Input electric power	Gross production	Participation of gross production (%)
Import - export balance	32.24	32.24	17.6%
Coal	4.16	1.42	0.8%
Nuclear	204.60	68.22	37.2%
Fuels	1.90	0.57	0.3%
Natural gas	105.09	57.75	31.5%
Non-renewable waste	3.75	1.44	0.8%
Renewable energy	24.85	21.65	11.8%
Hydropower	16.06	16.05	8.8%
Renewable waste	2.88	0.59	0.3%
Biogas	1.61	0.71	0.4%
Biomass	0.01	0.00	0.0%
Wind power	3.29	3.29	1.8%
Photovoltaic solar	1.01	1.01	0.6%
Thermoelectric solar	-	-	0.0%
TOTAL	376.60	183.29	100.0%

Table 5. Generation of electricity by type of energy, 2020. Source: (Institut Català d'Energia, 2012)

Electricity generation 2020 (PJ)	Input electric power	Gross production	Participation of gross production (%)
Coal	-	-	0.0%
Nuclear	255.50	86.83	40.2%
Fuels	2.25	1.29	0.6%
Natural gas	81.68	45.65	21.1%
Non-renewable waste	0.56	0.34	0.2%
Renewable energy	111.89	81.98	37.9%
Hydropower	20.77	20.77	9.6%
Renewable waste	6.14	1.12	0.5%
Biogas	5.66	3.12	1.4%
Biomass	17.07	3.75	1.7%
Wind power	45.00	44.99	20.8%
Photovoltaic solar	5.10	5.10	2.4%
Thermoelectric solar	12.15	3.13	1.4%
TOTAL	**451.88**	**216.08**	100.0%

Table 6. Comparison of energy consumption by 2020 for different demographic scenarios

		Population	Low scenario 7,034,076		Mid scenario 7,342,800		High scenario 7,596,347	
	Levels	Met. rate (MJ/h)	Hour	PES (TJ)	Hour	PES (TJ)	Hour	PES (TJ)
N	SOCIETY	15.0	6.16E+10	880,062	6.43E+10	961,855	6.65E+10	1,051,045
N-1	HOUSEHOLDS (HH)	1.7	5.65E+10	95,367	5.86E+10	99,018	6.03E+10	101,831
N-1	PAID WORK (PW)	151.2	5.16E+09	784,695	5.71E+09	862,837	6.26E+09	949,214
N-2	Services (SG)	74.0	3.75E+09	276,761	4.14E+09	306,637	4.55E+09	334,933
N-3	Transportation (TR)	745.4	2.75E+08	204,917	3.05E+08	227,272	3.32E+08	247,675
N-3	Other services (SE)	20.7	3.47E+09	71,843	3.84E+09	79,365	4.22E+09	87,257
N-2	Primary production (PS)	355.1	1.42E+09	507,934	1.57E+09	556,200	1.71E+09	614,282
N-3	Agriculture (AG)	167.6	1.15E+08	19,236	1.39E+08	23,274	1.41E+08	23,571
N-3	Industry (IN)	133.9	1.26E+09	168,204	1.38E+09	184,504	1.52E+09	203,216
N-3	Energy (ES)	7,055.4	4.54E+07	320,494	4.94E+07	348,421	5.49E+07	387,494

Table 7. List of acronyms

Acronym	Definition
EC	Energy consumption
EMR	Energy metabolic rate
EROI	Energy return on investment
ES	Energy and mining sectors
ET	Energy throughput
GDP	Gross domestic product
GHGs	Greenhouse gases
HA	Human activity
HH	Household
IDAE	Instituto para la Diversificación y Ahorro de la Energía
IER	Intensiu en Eficiència Energètica i Energies Renovables
IN	Industry
MJ	Megajoule
MuSIASEM	Multi-Scale Integrated Analysis of Societal and Ecosystem Metabolism
MW	Megawatt
PECAC	Pla de l’Energia i Canvi Climàtic de Catalunya
PES	Primary energy source
PS	Productive sectors
PW	Paid work
RE	Renewable energy
SG	Service and government
TET	Total energy throughput
THA	Total human activity
TJ	Terajoule
TR	Transportation