A methodology for the development of urban energy balances: Ten years of application to the city of Madrid

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ABSTRACT

This paper presents a methodology for the development of urban energy balances, which has been applied to the city of Madrid for the last ten years and is consistent with the guidelines of the International Energy Agency. The methodology is structured into three major modules: energy imports into the municipality, energy generation from either internal or external sources, and final energy consumption.

The paper shows results for the most recent year for which data are available, as well as historical series for the period 2006–2015. It also includes a comparison of the main energy indicators with the national situation.

The experience acquired during the ten years performing the energy balance in Madrid served to improve both the greenhouse gases and the air pollutant emission inventories, keeping their consistent with the energy balance, as well as to diagnose the city's current energy situation. This assessment was used to define a series of policies, energy saving and diversification measures, collected in different municipal plans, with the aim of decreasing the external energy dependence and the energy consumption, thereby lowering greenhouse gases emissions. Maintaining the same methodology and updating the historical series each year also allowed tracking the city's energy policy, as well as the evolution of the main energy indicators (i.e. per capita consumption and energy intensity). The methodology could be replicated in other cities worldwide, yielding improvements in their urban emission inventories.

Keywords:

Urban energy balance
Local decision-making tool
GHG inventory
Energy consumption

1. Introduction

It is undeniable that cities have gradually acquired more importance on the global stage in recent decades. In 2014, the population of the world living in urban settlements was estimated to be 54.5% of a total of 7.4 billion inhabitants. By 2030, urban areas are projected to host 60% of people globally (UN, 2014).

Cities occupy 3% of the planet's surface, but account for represent 67% of global primary energy demand (IEA, 2017). The combined effect of growing demand and depleting resources, as well as energy dependency, makes necessary a profound knowledge of energy supply and demand (OECD/IEA, 2005). Nowadays, the energy system is highly dependent on fossil fuels (Webb et al., 2016), with the ensuing consequences on air quality (AQ) and global warming (IEA, 2017).

Increasing evidence of climate change (CC) and a growing dependence on energy has underlined the European Union's (EU) determination to become a low energy economy and to have the energy consumed be secure, safe, competitive, locally produced and environmentally friendly (EC, 2008, 2010). Although cities are not

represented by an institution in the EU, local administrations are key to managing the challenges and opportunities offered by cities, which play an emerging role in responding to CC and in driving low carbon energy transitions (COM, 2018; Haarstad, 2016; IEA, 2016; Rosenzweig et al., 2010). Although they can act with varying degrees of autonomy, depending on the existence of decentralized energy planning (Parshall et al., 2010), municipal authorities are frequently better positioned to act with greater flexibility and effectiveness than central governments (Dent et al., 2016). Local authorities can prepare action plans, awareness campaigns and specific measures to achieve more sustainable transport or buildings (Poggi et al., 2017). This has also led to the emergence of horizontal forms of co operation and alliance formation through city networks such as the C40 Large Cities Climate Group and ICLEI Local Governments for Sustainability, as well as city stated plans like Agenda 21, which attempt to develop CC responses (Haarstad, 2016; Dent et al., 2016).

There are many factors that can determine the energy use distribution in a city, among which are climate, global economic position, consumption patterns, quality of the built environment, urban form and

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density and transport systems (Bhattacharyya, 2011). Therefore, it is important to understand which sectors consume more energy so as to take appropriate measures for emissions reduction (UN HABITAT, 2008).

A growing number of studies are reporting local energy consumption, which can be divided into two broad categories: (1) those focused on specific sectors of energy use and its patterns, and (2) those that analyse total energy consumption. The former is frequently focused on the building sector (Howard et al., 2012; Moghadam et al., 2018; Niu et al., 2011; Baynes et al., 2011; Zhao et al., 2012; Pereira & de Assis, 2013), although other studies also analyse the transport sector (Holden & Norland, 2005; Fichera et al., 2016) or density patterns (Steemers, 2003). They normally use a combination of downscaling, aggregation, weighting or GIS statistical approaches to estimate consumption, and regression models that relate energy consumption to physical, economic and social aspects of the urban environment.

The second group of studies usually classifies total energy consumption by end use. Phdungsilp (2010), Yu et al. (2015) and Winkler et al. (2017) used the Long Range Energy Alternatives Planning (LEAP) modelling tool to simulate a range of energy policies and to predict future energy and carbon scenarios. Cai et al. (2013) did a comparative study of economy structure, energy supply and carbon emissions among a few cities, including Beijing and London. Marshall et al. (2010) used the Vulcan data to measure energy consumption and related CO₂ emissions in urban areas in the United States. Liu et al. (2017) developed a simplified greenhouse gas policy assessment model (GHG PAM) based on the structure of annually updated and published OECD/IEDA energy balance (EB) tables. Most of these studies use data from multiple sources and energy statistics without explaining the methodology used, excluding the study by Gómez Ceballos & Morán Perafá (2015).

The originality and novelty of this work lies in the proposal and description of an EB methodology that allows collecting the energy information of a city and structuring its flows. Energy balances are a source of reliable and consistent information on the energy situation of a region and provide an analysis of the past and present status. Preparing an energy balance requires a large amount of historical data, such as 1) energy use by sector, 2) energy production, transformation and delivery to final users, 3) technical and operating statistics of the plants and installations, 4) financial and cost information, and 5) macro economic and other social information (Bhattacharyya, 2011).

This structure allows using real energy consumption data to perform a comprehensive energy assessment of the city. The information extracted from the EB is very helpful in preparing emission inventories and energy projections. Moreover, it is the starting point for the decision making process, which allows producing regulations and action plans on sustainable energy use, CC mitigation and AQ improvement.

The objectives of this paper are to 1) describe the EB methodology, 2) apply it to a case study (city of Madrid), 3) present the results obtained, considering the lessons learnt from 10 years of experience, and 4) show the importance and main applications of the EB.

2. Methodology

2.1. General structure

The methodology is based on a general energy generation/consumption model, following the guidelines of the International Energy Agency (OECD/IEA, 2005) and the Spanish Ministry of Energy (MINETAD, 2018). It establishes three modules (Fig. 1):

- Module 1: external energy sources. It includes imports of energy sources that can be directly consumed as final energy or used in energy transformation processes (e.g. refining, power generation and combined heat and power (CHP)).
- Module 2: internal energy sources. It includes local energy sources like municipal solid waste (MSW) and sewage sludge (SS). These

Fig. 1. General structure of the methodology proposed.

energy sources can be also used as final energy, but they are commonly used in electricity generation.

- Module 3: final energy consumption. It includes the energy consumption of fuels, electricity and renewables in the final sectors (residential, commercial, industry, transport, etc.).

The common energy unit used is tonne of oil equivalent (toe, 1 toe < > 41,868 MJ).

2.2. Case study

Madrid had a population of 3,141,991 inhabitants in 2015 (INE, 2017), making it one of the most populated cities in the EU and in the top ten European regions with the highest gross domestic product (GDP) per capita (AM, 2013a). With barely 0.1% of the national area (606 km²), it is the most populated city and is home to 6.7% of the Spanish population.

Madrid is one of the country's most important economic, commercial, financial and cultural centres (GDP of €95,236 million in 2015, 11.7% of Spain's GDP) (AM, 2017a).

The energetic specificities of the city are the following:

- Few sources of primary energy. The city lacks fossil fuel reserves and only has renewable resources like solar, geothermal and wind energy, as well as the waste valorisation.
- No large energy transformation plants for power generation or fuel production (refineries).
- Reduced electricity generation: MSW valorisation, CHP and renewable sources.
- Elevated final energy consumption. The city acts as an energy sink, as it is necessary to import a high quantity of energy to satisfy the final demand.
- "Barajas effect". A high quantity of kerosene is supplied to the Adolfo Suárez Madrid Barajas airport, which is reflected in the total energy imports. However, only a fraction is really consumed on aircrafts within the city boundaries. In the case of Madrid, only kerosene used in Landing and Take Off (LTO) cycles was considered as final energy consumption in order to be consistent with the local GHG and Air Pollutant Emission Inventory. LTO cycles include all activities near the airport that take place below a height of 914 m, whereas "cruise" is defined as all the activities that take place above 914 m (EEA, 2016). However, there are other methodologies to allocate fuel consumption for GHG emission estimation with different criteria, such as Global Protocol for Community Scale GHG Emission Inventories (WRI, 2014), Publicly Available Specification (PAS)

Fig. 2. Simplified flow chart of the proposed methodology for the EB of the city of Madrid.

2070:2013 of the British Standard Institution (BSI, 2013) and International Organization for Standardization 37120:2018 (ISO, 2018).

Due to a lack of information, energy losses in storage and transport operations were not considered within the city boundaries. Although losses may occur in operations such as refuelling, distribution and storage of liquid, solid or gaseous fuels, as well as in electricity transport/distribution, they were not imputed to the city since their detailed quantification depends on unavailable information, including facility characteristics and operability (AM, 2017a).

The general structure of the methodology was adapted to the case study characteristics as shown in Fig. 2.

2.2.1. External energy sources: imports

Energy imports represent the largest part of the final energy consumption. The imported sources are:

- Coal and biomass, mainly consumed in the Residential Commercial Institutional (RCI) sector.
- Natural gas, directly consumed (as final energy), as fuel for electricity generation or as auxiliary fuel in other processes (as primary

Fig. 3. Location of coal boilers in the city of Madrid (AM, 2015).

Table 1
EB key information and its sources.

Key parameters/Information	Key information sources
Coal, biomass and diesel boilers: location and consumption (Fig. 3 shows coal boilers example)	Madrid Council Home and industrial boiler inventory (prepared and maintained by the research team) (AM, 2015)
Electricity consumption by activity	Municipal statistics. Energy (AM, 2018a)
Fuel consumption of MSW collection vehicle fleet, municipal buses and other municipal fleets: oil products, biofuels and natural gas consumption	General Directorate of Sustainability and Environmental Control ^a
Energy consumption and generation from WW treatment plants	General Directorate of Water Management ^a
Energy consumption and generation from MSW treatment plants	Parque Tecnológico de Valdemingómez (AM, 2016)
GDP data	General Directorate of Statistics ^a
Total oil products (including additives), biofuels, natural gas and biomass consumption	Commercial distributors^a
Thermal solar (square metres of panel and energy production) and geothermal (power and energy production)	Madrid Regional Government
Photovoltaic energy production and CHP data (when electricity for self-consumption is not available, 10% is considered)	General Directorate of Industry and Energy ^a
Population	Spanish Regulator of Markets and Competitiveness^a
Aircraft operations data (number of operations by type of aircraft)	Spanish National Statistics Institute (INE, 2017)
Mapping between aircrafts and types of engines	Aeropuertos Españoles y Navegación Aérea (AENA, 2017)
Aircraft consumption by engine and cycle	International Civil Aviation Organization (ICAO, 2017)
Specific consumption and/or generation data for industrial plants	Industrial plants (via questionnaires) ^a

^a No public data and directly supplied.

energy to produce electricity).

- Oil products: liquefied petroleum gases (LPG), gasoline and its additives (methyl tert butyl ether, MTBE, and ethyl tert butyl ether, ETBE), gasoil A (road transport), B (agricultural uses) and C (heating and industry), fuel oil and kerosene (all fuel supplied to Madrid Airports). In the case of biofuels, they can be used pure or mixed with gasoline or gasoil (bioethanol and biodiesel, respectively). When biofuels are mixed, it is necessary to know the percentage of each fraction. The percentage of MTBE and ETBE in gasoline is also needed.

The imported electricity is calculated by subtracting the total electricity from the grid minus the electricity generated in the city (CHP, MSW incineration, biogas use, etc.) that is reverted to the grid. The net electricity production is the difference between the gross production of each plant minus its self consumption.

2.2.2. Internal energy sources and energy production

The energy generation comes from the use of internal energy sources and CHP using imported energy sources (external sources):

- From internal energy sources: renewable sources and MSW valorisation. Solar (thermal and photovoltaic) and geothermal energy production plants are considered. In the MSW incineration plant (waste to energy plant), located in the Parque Tecnológico de Valdemingómez (PTV), the net electricity produced is reverted to the grid. In addition, the PTV complex has two MSW biomethanization plants, in which one part of the biogas produced is refined and injected into the natural gas distribution network, and the other part is energetically valorised in combination with landfill biogas to produce electricity. Furthermore, the biogas generated in the anaerobic digestion of SS is used in power production for self consumption.
- From external sources: CHP plants in the RCI sector and industry, as well as two CHP plants located in the waste water (WW) treatment plant (SS drying plants). In these CHP plants, natural gas is the most common auxiliary fuel, although others can be used. The fraction of natural gas used to generate electricity is not considered as final energy; only the fraction used with thermal applications.

2.2.3. Final energy consumption

It is divided into six activity sectors:

- RCI. It includes the energy consumed by the residential sector (dwellings), commercial sector (both large and small businesses) and institutional/services sector (offices, public administrations).
- Industry. It includes the final energy consumed by industrial activities.
- Road transport. Energy consumed by road vehicles.
- Non road transport. It includes the energy consumed by air transport, railway and mobile machinery used in civil construction, industry and agriculture. The estimation of kerosene consumed by aircrafts during LTO cycles is calculated by considering the number of operations by aircraft type (AENA, 2017) and the kerosene consumption in an LTO cycle by aircraft engine type (ICAO, 2017).
- MSW treatment. It includes the energy consumed by the activities related to MSW management, as well as LPG consumption of cremation. Natural gas and gasoil C consumption in biogas valorisation and waste to energy plants, respectively, must not be computed as final energy because they are auxiliary fuels used in the production of electricity.
- WW treatment. It includes the activities related to WW treatment, including SS drying plants. Only the fraction of natural gas used to heat production must be computed as final energy.

2.3. Data compilation and information sources

The next step in calculating the EB is to identify and compile the necessary information, which is provided by either local, regional or national data sources (Table 1). When real data are not available, it is necessary to make an estimation considering the information collected in other years, provided that the historical data series are consistent.

3. Results and discussion

3.1. Year 2015

3.1.1. Imports

As Table 2 shows, the city is highly dependent on products (63.2%). Electricity contributes 20.3% and natural gas 15.4%. The importation of fossil sources is predominant in Madrid, although only 10% of all the kerosene imported by the airports is computed as final consumption within the city boundaries, corresponding to the fraction consumed in LTO cycles.

Table 2
Energy imports in Madrid, 2015.

Energy source	ktoe	%
Natural gas	794.83	15.43
Oil products	3255.31	63.18
LPG	32.84	0.64
Gasoline	220.75	4.28
Gasoil A + B	680.95	13.22
Gasoil C	153.68	2.98
Fuel oil	0.36	0.01
Kerosene	2144.66	41.62
Gasoline additives	22.08	0.43
Biofuels	29.95	0.58
Biodiesel	29.94	0.58
Bioethanol	0.01	0.00
Electricity	1046.15	20.30
Coal	19.88	0.39
Biomass	6.51	0.13
Total	5152.63	100.00

Table 3
Electrical and thermal energy generation, 2015.

Energy source	Generation	
	ktoe	%
Electricity generation	53.70	80.27
MSW incineration	15.27	22.83
Biogas ^a	11.39	17.03
Photovoltaic solar	1.94	2.90
CHP	25.10	37.52
Thermal energy	13.21	19.75
Thermal solar	12.90	19.28
Geothermal	0.31	0.46
Total	66.90	100.00

^a Biogas from landfill, MSW biomethanization and anaerobic digestion of SS.

3.1.2. Internal energy sources and energy production

The energy generation is shown in Table 3. As mentioned in Section 3.2, energy generation in the city (66.9 ktoe) was much lower than the energy imports (5152.6 ktoe; Table 2), accounting for 2.1% of final energy consumption (3230.5 ktoe; Table 4). The city of Madrid is a typical example of the urban energy behaviour in the West: it acts as an “energy sink” characterized by high energy consumption and low generation. To reduce energy dependence, this kind of city must make a greater effort in terms of energy efficiency, increasing the use of its own energy sources. Moreover, the use of its own sources provides security of supply and contributes to lower energy losses in transport operations.

CHP is the source that most contributed to energy generation (37.5%), although MSW incineration was the greatest one among the internal energy sources (22.8%). In this last case, electricity generation depends on the calorific value of MSW ($14.6 \text{ GJ/t}_{\text{MSWincinerated}}$) and the energy efficiency of the waste to energy plant (17%).

Electrical power generation accounted for 80.3% (4.9% of final

electricity demand; 53.7 vs. 1099.8 ktoe; Table 4), whereas thermal generation was 19.8%. 74.2% of all the electricity produced was reverted to the grid, whereas the rest was self consumed in the generation plants.

3.1.3. Final energy consumption

Final energy consumption in 2015 was 3230.5 ktoe, a breakdown of which is shown in Table 4. The RCI sector was the main energy consumer (54.7% of the total consumption), 1768.2 ktoe: 52.8% was electricity, 35.3% natural gas and 9.7% oil products (gasoil C and LPG), the latter two used mainly for heating and hot water.

The city's central location in the Iberian Peninsula influences the extensive transport infrastructure grids that effectively interconnect the regional, national and international territory. Consequently, road transport was the second consumer in the city (968.8 ktoe). Within this sector, 93.2% of consumption corresponded to oil products, 3.7% to natural gas and 3.1% to biofuels.

The non road transport sector consumed 310.7 ktoe, where 71.3% were oil products (62.6% kerosene and 8.8% gasoil B) and 28.7% was electricity. The local railway network connects the city to the outskirts using a radial structure and the underground network is the third most extensive in Europe (after London and Moscow). Regarding air transport, the Adolfo Suárez Madrid Barajas airport is one of the busiest in Europe and the most important in Spain, with 366,608 operations in 2015 (AENA, 2017).

By contrast, the industry sector only contributed 5.2% (168.3 ktoe), with publishing and graphic arts, as well as the automotive industry, being the most relevant industrial activities (AM, 2013a). This sector has experienced a significant decrease in recent years, similarly to cities such as Berlin and Tokyo, where the industry sector consumes < 10% of the energy because economic activities have shifted from industry to services (UN HABITAT, 2008). The service sector is the main activity in the city, comprising 85.9% of local economic activity (AM, 2013a).

Finally, the WW treatment and MSW treatment sectors represented 0.3% and 0.2%, respectively. In 2015, 251,137,696 m³ of WW was treated in the eight treatment plants that serve Madrid (AM, 2017b). In addition, 1,200,928 t of MSW was produced, 5.5% of Spain's MSW production (INE, 2018). The per capita MSW production rate of Madrid was 382 kg/inhab year, compared to 464 kg/inhab year at the national level (INE, 2018). All MSW was sent to PTV (Pérez et al., 2018).

3.2. Period 2006–2015

3.2.1. Imports

Total imports decreased by 11.9% in this period (Table 5). In general, the distribution of energy sources did not change significantly, although the specific contribution of natural gas decreased (15.4% in 2015 versus 16.8% in 2006), and electricity increased. Regarding oil products, there was a downward trend (11.6% in the whole period), except in 2015, when it increased by 4.8% compared to 2014. One of the objectives of the municipality is to reduce oil products by 20% in

Table 4
Final energy consumption by sector and energy source (ktoe), 2015.

Energy source	RCI	Industry	Road transport	Non-road transport	MSW treatment	WW treatment	Total	%
Biomass	6.51	–	–	–	–	–	6.51	0.20
Natural gas	624.11	96.85	36.04	–	–	–	756.99	23.43
Oil products	170.57	9.06	902.76	221.63	0.12	–	1304.14	40.37
Biofuels	–	–	29.95	–	–	–	29.95	0.93
Electricity	933.96	62.37	0.03	89.05	4.92	9.51	1099.84	34.05
Coal	19.88	–	–	–	–	–	19.88	0.6
Thermal solar	12.90	–	–	–	–	–	12.90	0.40
Geothermal	0.31	–	–	–	–	–	0.31	0.01
Total	1768.24	168.28	968.77	310.67	5.05	9.51	3230.52	100.00
%	54.74	5.21	29.99	9.62	0.16	0.29	100.00	

Table 5
Energy imports in the period 2006–2015.

Year	Natural gas		Oil products		Electricity		Other sources ^a		Total	
	ktoe	%	ktoe	%	ktoe	%	ktoe	%	ktoe	%
2006	982.46	16.79	3682.91	62.94	1145.29	19.57	40.39	0.69	5851.05	100.00
2007	1035.27	17.22	3744.68	62.29	1170.63	19.47	61.54	1.02	6012.12	100.00
2008	1058.86	17.44	3745.28	61.69	1200.44	19.77	66.69	1.10	6071.27	100.00
2009	977.18	16.76	3566.35	61.17	1185.96	20.34	100.56	1.72	5830.05	100.00
2010	897.89	15.64	3567.13	62.13	1168.96	20.36	106.98	1.86	5740.96	100.00
2011	814.46	14.53	3554.17	63.40	1130.39	20.16	107.26	1.91	5606.28	100.00
2012	927.67	17.00	3317.89	60.81	1108.72	20.32	101.48	1.86	5455.76	100.00
2013	942.58	18.39	3069.00	59.88	1058.37	20.65	55.45	1.08	5125.40	100.00
2014	813.09	16.20	3106.72	61.91	1041.01	20.74	57.56	1.15	5018.39	100.00
2015	794.83	15.43	3255.31	63.18	1046.15	20.30	56.34	1.09	5152.63	100.00
% change 2006–2015		19.10		11.61		8.66%		39.47		11.94

^a Including biofuels, biomass, coal and hydrogen.

2020 with respect to 2011, excluding kerosene (AM, 2014). In 2015, the reduction was 6.9%.

3.2.2. Internal energy sources and energy production

Energy generation decreased by 5.3% in this period (Fig. 4). The sharp reduction since 2014 was due to the closure of two SS drying plants. However, CHP still accounted for 37.5% of total energy generation in 2015. The electricity generation in MSW incineration decreased by 17.8% due to the fluctuation in the quantity and composition of incinerated MSW. Furthermore, energy generation from biogas valorisation decreased by 20.3%, because of falling biogas extraction at the closed landfill in PTV. The landfill currently in use does not produce significant amounts of biogas.

On the other hand, solar (photovoltaic and thermal) energy gradually increased its contribution to the total generation, totalling 22.2% in 2015 versus 3.3% in 2006. Geothermal energy is still in an emergent stage (0.3%), although an effort is being made to study the viability of this technology in more locations. Electrical power generation accounted for 4.8–7.6% of the total electricity consumed in the period. An objective of the municipal energy plan (AM, 2014) is to self generate 10% of the final energy demand in 2020. However, this value stood at 2.1% in 2015. This plan seeks to promote the development of high efficient district heating and cooling systems, the integration of renewable generation systems in new and existing buildings, and the improvement of MSW valorisation.

3.2.3. Final energy consumption

This parameter went down by 16.1% in the period evaluated

(3852.7 to 3230.6 ktoe) (Fig. 5.). This decrease is due to the combination of two factors: i) saving and energy efficiency policies implemented by the local government and ii) the effect of the economic crisis that Spain suffered starting in 2008.

Oil products were the main energy source (40.4% in 2015), although in 2006 their contribution was 43.3%. Natural gas consumption decreased by 18.3% since 2006, although the gas supply network in operation experienced an increment of 35.1% (4427 km in 2015), denoting a more efficient use (AM, 2018b).

Coal consumption experienced a gradual decrease in RCI heating due to its substitution by natural gas, leading to a 48.6% reduction since 2006 (contribution of 0.5% in 2015). In addition, biofuels decreased substantially from 2012 to 2013 due to the municipal bus fleet's shift away from biodiesel.

The RCI sector accounted for 54.7% of final energy consumption in 2015, followed by road transport with 30%. However, both cases saw a decrease in consumption of 10.2% and 14.9% compared to 2006, respectively. The industry sector has a cumulative decrease of 46.6% (Fig. 6).

Consequently, the planned energy saving and efficiency measures targeted the sectors that demand the most energy resources in the city: RCI and road transport. Regarding the RCI sector, the local objective is to reduce final energy consumption by 10% in 2020 with respect to 2011 (AM, 2014): a reduction of 3.1% was achieved in 2015. Other measures in the sector are the rehabilitation of existing buildings, the promotion of energy efficient new constructions and control and management in municipal buildings and infrastructures through energy service companies. One of the investments for reducing electricity

Fig. 4. Energy generation by source (2006–2015).

Fig. 5. Final energy consumption by source (2006–2015).

consumption was the replacement of 225,000 public lighting points with more efficient systems between 2014 and 2015, 85,000 of them with LED technology (AM, 2013b). Consequently, public lighting consumption decreased by 38.4% in 2015 compared to 2011 (reducing the contribution to final electricity consumption from 1.0% to 0.7%).

Regarding the road transport sector, the 2020 objective is to reduce GHG emissions by 20% with respect to 2011 (AM, 2014): a reduction of 3.6% was achieved in 2015. The most relevant measures were the promotion of distribution and supply infrastructure for alternative energy sources (natural gas, LPG and electricity); the reduction of energy consumption in public fleets and private vehicles; and the promotion of alternative transport modes (public transport, car sharing and bicycle).

3.2.4. Energy indicators

Per capita consumption was 1.03 toe/inhabitant in 2015 (43.05 GJ/inhabitant). It is a low value compared to other cities like New York, Beijing, Paris, Berlin, London, Rome, Tokyo or Lisbon, whose per capita consumption, according to Schulz (2010), ranges from 128.07 (New York) to 48.65 GJ/inhabitant (Lisbon). It decreased by 16.5% in the period 2006–2015, even though the population grew by 0.4% (Fig. 7). The decrease in final energy consumption also led to a decrease in energy intensity of 18.8% (33.92 toe/M€ in 2015), whereas the GDP rose by 3.2%. Regarding final energy intensity, the 2020 EU objective is to achieve a 20% reduction with respect to 2011 (which is supported by

the municipal action plan) (AM, 2014). In 2015, the decrease was 7% compared to 2011, thus requiring an additional 13% reduction of (2.6% per year) to achieve the 2020 commitment. The average reduction in 2011–2015 was 1.7% per year, so a greater effort is required.

A comparison with the national situation is included in Appendix A.

3.3. Reviewing/updating the EB

As a basic and critical point of the methodology, the whole historical series must be reviewed annually with the aim of updating the information, as well as checking for improvements and possible new data sources. This process is essential to consistently track compliance with the measures implemented during the period in question.

In order to illustrate the ten year process, the variation in final consumption in the first version of 2006 and the last version carried out for that year (in the 2015 EB, which includes the period 2006–2015) is shown in Table 6, yielding a change in final energy consumption of 4.4%.

The 7.5% increase in oil products is caused by different modifications: the inclusion of distributor data instead of estimating it (for LPG), specific information from individual plants (fuel oil, gasoil C), improved data quality in estimating the LTO cycles and the inclusion of boiler inventory data (gasoil C). Its inclusion, along with updated information, also modified the consumption of biomass and coal. Natural

Fig. 6. Final energy consumption by sector (2006–2015).

Fig. 7. Evolution of energy indicators (2006–2015).

Table 6

Differences in final energy consumption: year 2006 in the first and the last edition of EB.

Final consumption	2006 (2006 EB)	2006 (2015 EB)	%
Biomass	0.30	0.29	4.5
Natural gas	890.53	926.27	4.0
Oil products	1553.87	1670.11	7.5
Biofuels	1.40	1.39	1.0
Electricity	1213.81	1213.72	0.0
Coal	28.44	38.68	36.0
Thermal solar	2.22	2.22	0.0
Geothermal	0.00	0.00	–
Hydrogen	0.00	0.04	–
Total	3690.56	3852.72	4.4

gas has increased 4.0% due to various changes, among which are the inclusion of the consumption by the MSW collection fleet, the use of data from commercial distributors instead of municipal statistics and the inclusion of specific consumptions by industrial plants.

3.4. Applications

The EB is a key instrument for preparing GHG and Air Pollutant Emission Inventories (AM, 2018c), as well as for developing AQ and CC plans (AM, 2017c, 2014; Borge et al., 2014; Vedrenne et al., 2016).

The emissions inventory relies on the EMEP/EEA methodology, which is coordinated by the European Environment Agency (EEA, 2016) and meets the requirements established by the Intergovernmental Panel on CC (IPCC, 2006). It includes an estimation for acidifying gases, ozone precursors, particulate matter and GHG emissions. In turn, GHG emissions are disaggregated in direct emissions (within the city boundaries, scope 1 emissions as per BSI (2013, 2011) and WRI (2014)), and indirect emissions of electricity consumption (scope 2, emissions as per BSI (2013, 2011) and WRI (2014)) and losses in transport (scope 3, emissions as per BSI (2013, 2011) and WRI (2014)).

The evolution of both final energy consumption and total GHG emissions by sector is shown in Fig. 8. Note the close relationship between them, which is why constant feedback is needed (it is important to realize that not all GHG emissions are related to energy use). In 2015 GHG emissions were 11,232 t CO₂ eq (AM, 2018c), a 27.9% decrease

since 2006 (the decrease in energy consumption was 16.1%). The rate of emissions per capita decreased by 28.2% (3.6 t CO₂ eq/inhabitant) and the emissions intensity per unit of GDP fell 30.2% (118 t CO₂ eq/M € in 2015).

In the last ten years, the EB has been a useful tool for decision making regarding environmental policy, as well as an essential element for gaining a basic understanding of the activities affecting AQ, sustainable energy management and CC mitigation. It provides, in conjunction with the GHG and air pollution emission inventory, critical information to develop, implement and track policy initiatives and action plans at the municipal level (AM, 2017c, 2014).

In 2008, Madrid joined the Covenant of Mayors for Climate and Energy (COM), a European initiative that brings together thousands of local governments voluntarily committed to improving energy efficiency and using renewable energy sources with the aim to comply with EU climate, energy and AQ objectives (Monforti Ferrario et al., 2018). The signatory cities of the COM are required to submit a Baseline Emission Inventory and a Sustainable Energy and Climate Action Plan (SECAP) (COM, 2016), for which the EB is a crucial input.

4. Conclusions

This manuscript presents a structured methodology for preparing an EB, beyond the annual statistics published by different government agencies and energy companies. This methodology yields detailed knowledge of the energy generated and consumed in a city (by energy source and use), compared to the use of aggregated regional or national EB. Moreover, the development and annual revision of data management and collection procedures allow optimizing the continuous improvement process, as well as the representativeness and quality of the data.

During its ten year application to the city of Madrid, the EB has been essential to preparing a consistent GHG and air pollution emissions inventory. Together, these tools provided strategic information to the City Council, facilitating the policy making process and allowing it to properly plan and implement measures related to energy saving and energy efficiency, in order to mitigate CC and improve AQ.

Through its energy and CC plan, the city of Madrid set a group of objectives for 2020 in terms of reducing final energy consumption (saving and energy efficiency), increasing internal energy generation (reduced dependence on external energy, improved level of self

Fig. 8. Final energy consumption and GHG emissions by sector (2006–2015).

sufficiency and security of supply) and increasing renewable energy use. The balance showed that, in order to reach these objectives, the city of Madrid should eliminate coal consumption in the RCI sector, as well as increase its energy efficiency. Therefore, the EB showed that an effort to improve insulation and heat and hot water systems in buildings was necessary. Regarding road transport, the EB illustrated the need to further promote public transport, as well as to develop more efficient and environmentally friendly alternative energy sources.

This methodology is an easy to implement tool that could be applied to other cities (e.g. cities along the world which have not yet developed an EB).

Some limitations were found during this study. The first one involves the lack of specific information on the energy distribution losses within city boundaries (electricity and fuels). The research team is working on this for upcoming editions. Another limitation is related to aircraft fuel consumption and the differences between the methodology considered in this study and others, such as [WRI \(2014\)](#), [BSI \(2013\)](#) and [ISO \(2018\)](#). In future studies the research team will carry out a

comparison between methodologies. Another limitation involves the arduousness of collecting the vast amount of data needed at the city level. However, some specific data could be assumed using average values.

Finally, the one and half year lag in the study (necessary to collect the required information) delays an immediate assessment of the effect of the measures implemented in the EB. Despite this, the EB is a strong monitoring tool for assessing the application of improving measures and for evaluating the degree of compliance with the city's energy objectives.

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Appendix A. Comparison with national situation

In 2015, the main final energy source consumed in Madrid was oil products, accounting for 40.4% of all consumption, although this figure was higher (52.7%) at the national level ([Table A1](#)). The contributions of electricity and natural gas were 34.1% and 23.4%, higher than in Spain as a whole (22.8% and 16.9%, respectively). At the sector level, the RCI and transport sectors were the main consumers in Madrid, with a contribution of 54.7% and 39.6%, whereas in Spain these sectors accounted for 34.8% and 41.6%, respectively. The greatest difference lies in the industry sector, since the contribution in Madrid was considerably lower than in the rest of Spain (5.7% versus 23.5%). This is because the energy consumption structure in Madrid is based on the services sector, which is less energetically intensive than industry.

Madrid covers 0.1% of the national surface, but has 6.7% of the total population. Per capita consumption in Madrid was 45.4% lower than in the rest of Spain (1.03 versus 1.88 toe/inhabitant), among other reasons, because of the lack of heavy industry. Energy intensity was also lower in Madrid (33.9 versus 107.4 toe/million €).

Table A1

Final energy consumption of Madrid and Spain, 2015.

By energy source					
Energy source	Madrid		Spain		% Madrid/Spain
	ktoe	%	ktoe	%	
Coal	19.88	0.62	1399	1.59	1.42
Oil products	1304.14	40.37	46,247	52.71	2.82

(continued on next page)

Table A1 (continued)

By energy source					
Energy source	Madrid		Spain		% Madrid/Spain
	ktoe	%	ktoe	%	
Natural gas	756.99	23.43	14,792	16.86	5.12
Electricity	1099.84	34.05	19,999	22.79	5.50
Renewable energy	49.66	1.54	5302	6.04	0.94
Total	3230.52	100.00	87,739	100.00	3.68
By sector					
Final sector	Madrid		Spain		% Madrid/Spain
	ktoe	%	ktoe	%	
RCI	1768.24	54.74	30,550	34.82	5.79
Transport	1279.45	39.61	36,542	41.65	3.50
Industry	182.83	5.66	20,647	23.53	0.89
Energy indicators					
Parameter	Madrid		Spain		% Madrid/Spain
Surface (km ²)	606		505,990		0.12
Population (inhabitants)	3,141,991		46,624,382		6.74
GDP (M€)	95,236		816,971		11.66
Energy intensity (toe/M€)	33.92		107.40		–
Per capita consumption (toe/inhabitant)	1.03		1.88		–

Regarding the evolution of energy indicators in the period 2006–2015 (Fig. A1), we see that per capita consumption in Madrid decreased by 16.5%, due to a 16.1% decrease in final energy consumption and a 0.4% increase in population. Nationally, the decrease was 18.4%. Energy intensity in Madrid decreased by 18.8% (20% nationally) as a consequence of the trend in final energy consumption, and the 3.2% increase in GDP.

Fig. A1. Evolution of energy indicators for Madrid and Spain (2006–2015).

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