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Electricity production using renewable resources in urban centres

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Previous research has identified 11 technologies that use resources that are available in or come from cities. It has been established that using these technologies, the flows from energy carriers required by cities could be reduced. These carriers can be electricity or fuels. Of the identified technologies, eight can produce electricity: biomass, biodigestor biogas, landfill biogas, waste incineration, tidal, small wind, small hydroelectric and photovoltaic technologies. The use of these technologies depends on the existence of resources and technical, economic and social or environmental factors. This research proposes the use of multiple-criteria techniques to select the most appropriate options for promoting renewable energy in cities. This approach was applied to the medium-sized city of Cuenca in Ecuador. Ecuador is a developing country, is an oil producer and has important water resources. The authors concluded that studies of the potential for implementing hydroelectric and solar photovoltaic energy and energy from landfill gas should be extended. The results coincide with the existing resources, implemented projects and the expectations of local professionals.

Notation

an	an alternative
C_1	cost of a power generation plant
ck	a criterion
Elec	generated electricity
$P(.,.)$	function of preference
p	scaling factor
r	discount rate
S_1	size of a power generation plant
T	number of hours that technology operates in 1 year
t	lifespan of renewable technology
α	Cronbach's alpha coefficient
$\pi(.,.)$	indicator of preference
ϕ	preference flow
ω	weight of each subcriterion

1. Introduction

Cities are a consequence of energy development that in addition to encompassing the majority of daily living for humanity, concentrate buildings, transportation, industrial processes and other human activities. More than 50% of the world's population live in urban areas, which occupy less than 3% of the earth's surface (Weisz and Steinberger, 2010). More than two-thirds of primary energy is consumed there. Cities cause between 70 and 80% of the emissions of greenhouse gases related to energy. By 2050, 66% of the world's population is expected to live in urban areas; thus, with the current energy model, more resources will be required, and environmental impacts are expected in consequence.

A city's infrastructure depends on the flow of goods, materials or services, which are mainly imported, exported or transformed and are inter-related through the economy and environment. The expectations of environmental deterioration and the effects of global warming demand a change in the way cities are conceived. An essential step is the need for public policies and organised planning that generate changes in inhabitants' attitudes (Agudelo-Vera *et al.*, 2012). Due to the significant impact that cities have on the environment, the proposed changes are opportunities for promoting sustainability (Kennedy *et al.*, 2012).

As a result of urban expansion and increasing energy demands, governments and international institutions have established objectives to make cities less aggressive towards the environment. In this regard, the UN General Assembly adopted the 2030 Agenda for Sustainable Development in September 2015. In particular, the aim is that cities become more resilient to climate change while boosting the economy and reducing poverty. Similarly, in the Conference on Housing and Urban Development Habitat III, which was held in October 2016 in Quito City, Ecuador's capital, the need to promote energy efficiency and the use of clean energy at the urban level were highlighted. Furthermore, it was recognised that cost reductions in renewable energies (REs) are a requisite to mitigate the consequences of global warming.

Several studies have compared electricity demands with the possibilities of RE supply. In Mar del Plata, Argentina, it was established that the use of forest residues (from pruning urban trees and garden maintenance) could supply 4·36% of the energy demand (Roberts *et al.*, 2015). In Tijuana, Mexico, it was estimated that landfill gas can provide 40% of the required electricity for public lighting services (Aguilar-Virgen *et al.*, 2014), whereas in Rio de Janeiro, Brazil, 25% of the city's energy could be supplied by burning urban solid waste (de Souza *et al.*, 2014). In Wageningen, the Netherlands, it is estimated that 12% of the electrical energy demand can be covered by wind power (Agudelo-Vera *et al.*, 2012). With hydroelectric power plants located along rivers, it is possible to meet the power demands of 29 000 households in Beppu City, Japan (Fujiia *et al.*, 2015). In Ludwigsburg, Germany, it is possible to produce 65% of the required energy with photovoltaics on roofs (Eicker *et al.*, 2014).

The above-mentioned cases demonstrate the interest in consolidating energy efficiency in cities. As in developed countries, there are initiatives in developing countries to change the current energy models based on energy systems that are highly impactful on and invasive of nature, such as large hydroelectric dams or fossil fuels.

1.1 RE in inner cities

Conditions for sustainable growth development are not possible without considering the regenerative capacities of materials and energy. The contradictions between economic growth and environmental protection are increasingly evident due to rapid industrialisation and urbanisation. On the one hand, the aim is a sustainable society, but on the other hand, the use of energy increases. This demonstrates the impossibility of society and its institutions implementing urban management that does not require abundant resources and that is based on austerity policies (Páez, 2010).

The challenge is to design sustainable cities that can be maintained by their own urban metabolic processes. The efficient performance of buildings is required, as is massive participation of REs. Using renewable technologies, inner cities can mitigate losses caused by transmission networks, avoid the construction of external infrastructures for generation and transport that occupy additional land, reduce pollution, reduce the heat island effect, improve quality of life and prevent interruptions in energy flows (IRENA, 2016). In addition, the work of the local people is promoted and constitutes a native resource, which has direct impact on the energy sovereignty of any country or region (Ren *et al.*, 2010). However, technical, economic and human resources, which are not always available, and urban planning have priorities other than promoting the use of renewable technologies at the urban level (Páez, 2010).

Unfamiliarity with energy potential or a lack of citizen interest should not hold back the promotion of structural changes in how the current energy models are conceived (Barragán and Terrados, 2017). To choose the most suitable technology for any city, the proposal is to use multiple-criteria methods that have been used for energy planning at national and regional levels (Terrados *et al.*, 2009).

1.2 Case study: Cuenca, Ecuador

The methodological proposal has been applied to Cuenca, Ecuador. This city is located in the Andes Mountains and near the equator (2° 39′ to 3° 00′ south latitude and 79° 54′ to 79° 20′ west longitude). The central urban area has an average elevation of 2560 m above sea level, but the overall urban area is located between 2350 and 2710 m above sea level. The city has a mild climate due to its altitude, which also results in daily temperature fluctuations, especially on sunny days. However, no seasons are observed due to its latitude. The temperature fluctuates from 24°C to a minimum of 8°C, but temperatures up to 30°C are typical on sunny days.

Cuenca is of medium size, and approximately 330 000 people live in the urban area. The population density is 4701 inhabitants per square kilometre. Electric power coverage reaches 98% of the population, and 96% have access to potable water. Solid waste collection services cover 99% of the demand, and waste is taken to a sanitary landfill. Of the population, 94% have sewer service, and most wastewater is sent to a treatment plant.

In 2016, the per capita energy requirement was 42·06 GJ/(inhabitant/year) (greater than the Ecuadorean per capita requirement of 35·44 GJ/(inhabitant/year)). This energy consumption is basically influenced by the transport sector, which accounts for 63% of the total energy consumption, followed by 21, 14 and 2% for the industry, residential and commercial sectors, respectively. The main energy sources are fossil fuels (gasoline 35%, diesel 32%, petroleum liquid gas 14%, fuel oil 6% and natural gas 3%), and electricity only contributes 10%. The main source of energy is fossil fuels, similar to the country's overall structure of consumption.

The average per capita consumption of electricity is approximately 1000 kWh/(inhabitant/year). The residential sector is the largest electricity consumer (38%), followed by the industrial and commercial sectors (24% apiece), urban lighting (7%) and others (7%).

A distributing company provides electric power to Cuenca City, and two electricity generation companies have been established. The electrical energy mix in Ecuador is composed of hydroelectric plants (49%) and thermoelectric plants (47%), and the remaining energy is provided by technologies such as wind, photovoltaics and biomass. The electrical energy that enters the city comes from external and distant plants, and there are no distributed generation systems.

2. Multi-criteria methods

The multiple-criteria decision analysis (MCDA) method was applied in this research. Wang *et al*. (2009) consider MCDA to be a useful tool for decision-making because it helps organise and synthesise information to identify the most suitable alternatives.

Multiple-criteria decision-making methods are applied to decide the best from an different alternatives. Options are evaluated according to ck criteria, choosing after comparing them (Wang *et al*., 2009).

There are different multiple-criteria methods, and for this work, those of interest allow the ordering of a limited number of alternatives. The outcomes for the same decision problem may vary from one method to another. Multiple-criteria techniques have the following steps in common: problem determination, suitable method determination, identification of alternatives, selection of criteria, decision matrix preparation, assignation, and alternative and decision-making prioritisation (Terrados *et al*., 2009).

2.1 Definition of the problem

RE resources can be obtained within a city and can therefore substitute for the consumption of electricity from external sources and fossil fuels. The focus is to detect different alternatives that are suitable for implementation under a set of criteria in places where there is insufficient information. Figure 1 outlines the new energy model against the current model (Barragán and Terrados, 2017).

2.2 Selection of a multiple-criteria method

The most popular methods in the field of energy planning are the AHP (analytical hierarchy process), Promethee (preference ranking organisation method for enrichment evaluation) and Electre (elimination and choice expressing reality). These methods evaluate the technological options and situations that include both renewable and conventional energies. Although the AHP method is simple, flexible and intuitive, it is difficult to apply when there are many criteria or alternatives. The Electre method allows comparisons of alternatives where there are no clear preferences, but the calculations are complex, and the best alternative occasionally cannot be defined. The Promethee method is simpler than Electre, and similar to AHP, it is easier to use, but it outperforms them. The Promethee method's primary problem is that it is subjective when qualitative criteria are used.

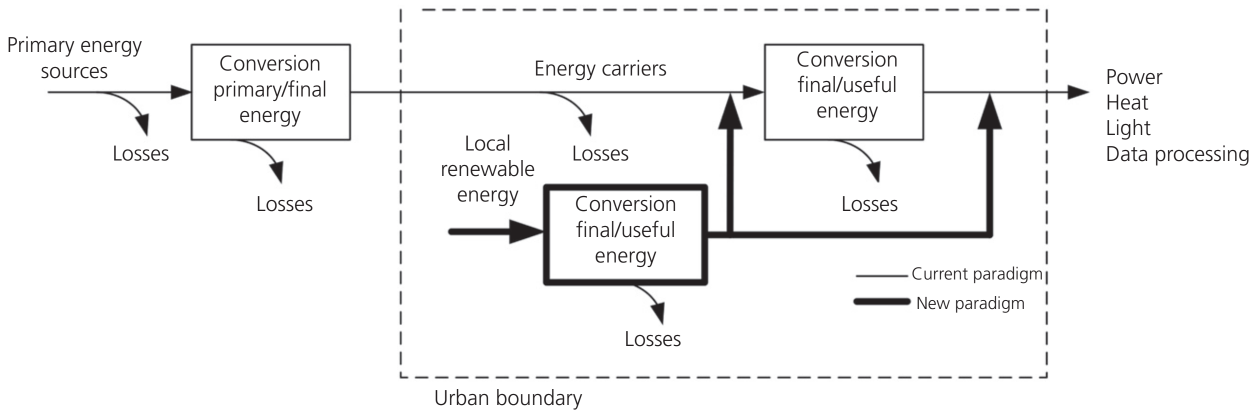

Figure 1. The current and suggested energy models (courtesy: WIT Press)

The literature review demonstrated that most studies using MCDA methods are conducted at the national and regional levels and have been marginally applied to cities. The Promethee method has been chosen based on the following considerations.

- The method is widely used for selecting energy technologies or scenarios.
- It enables alternatives to be ranked.
- Useful information for decision makers can be obtained.
- Qualitative and quantitative criteria can be used.
- The method is transparent and easy to understand.
- Free software is available for wide use.

The Promethee method was developed by Jean-Pierre Brans. It is an outranking method that selects or organises alternatives that may conflict with one another from different fields. Brans suggested the Promethee I and Promethee II versions. Jointly with Bertrand Mareschal, the III, IV, V and VI versions were developed. The application of the method and its versions have been explained in detail in several studies (Mareschal, 2013). Versions I and II allow partial and total ordering of alternatives and version III provides an interval order that emphasises indifference. Version IV extends the analysis to continuous sets of possible alternatives. Promethee V was proposed as a solution for multiple selection under constraints. Promethee VI allows the decision maker to explore the space of freedom by defining the upper and lower limits for the weight value of the criteria. The Promethee Gaia (geometrical analysis for interactive aid) graphic method is another version that provides a graphical representation of the alternatives against the criteria or subcriteria. The Promethee I, II and Gaia versions were used in this work.

This method identifies the preferred alternatives, different alternatives or incomparable alternatives. The non-dominant alternatives are more efficient. In addition, the Promethee method requires clear and precise information.

- Inter-criteria information: establishing weight values (ω) that reflect the importance of each criterion.
- Intra-criteria information, which is the information of each criterion.

Each criterion is assigned as a function of preference, which is the result of the deviation between the evaluation of alternatives for each criterion in particular. The method uses the so-called generalised criteria, which consist of associating each criterion, $c_j(\cdot)$, with a function of preference, $P_j(.,.)$. The preference indexes are then calculated between every two alternatives, $\pi(a_1, a_2)$. The degree of total preference for a_1 over a_2 is obtained with Equation 1.

1. $$\pi(a_1, a_2) = \sum_{j=1}^{k} P_j(a_1, a_2)\omega_j$$

where $P_j(a_1, a_2)$ is assigned as 1 if $a_1 > a_2$. ω_j indicates the importance of c_j.

The positive (ϕ^+) and negative (ϕ^-) preference flows for each alternative are the sum of the preference index of an alternative over the rest and of the rest over the alternative, respectively. One alternative will be greater than another as long as its positive flow is greater and its negative flow is smaller.

As specified, Equation 2 determines a partial ranking that identifies an alternative preference over another (Promethee I)

2. $$a_1 P a_2 \text{ if } \begin{cases} \phi^+(a_1) > \phi^+(a_2) \text{ and } \phi^-(a_1) < \phi^-(a_2), \text{ or} \\ \phi^+(a_1) = \phi^+(a_2) \text{ and } \phi^-(a_1) < \phi^-(a_2), \text{ or} \\ \phi^+(a_1) > \phi^+(a_2) \text{ and } \phi^-(a_1) = \phi^-(a_2) \end{cases}$$

The outranking flows were determined for each alternative (see Equation 3) such that the higher the net flow is, the greater the alternative will be (Promethee II).

3. $$\phi(a) = \phi^+(a) - \phi^-(a)$$

The Gaia plane is represented graphically by representing the alternatives by points and the criteria by vectors in a k-dimensional space. Each criterion is represented by an axis drawn from the centre of the Gaia plane. This analysis allows one to distinguish which alternatives are best under a particular criterion, as they will be located in the direction of the corresponding axis on the Gaia plane. Therefore, Equation 4 is used to determine the net flow $\phi_j(a)$ as influenced only by the $c_j(\cdot)$ criterion.

4. $$\phi_j(a) = \frac{1}{n-1} \sum_{a_1 \neq a_2} \left[P_j(a_1, a_2) - P_j(a_2, a_1) \right]$$

Large amounts of information are kept in this plane when the projection is carried out because it is possible to observe graphically the behaviours of the alternatives against the criteria utilised. The Promethee Gaia software program (Mareschal, 2016) was used for this study and enabled the decision-making process and the graphic visualisation of the results.

2.3 Identification of alternatives

Under the urban metabolic approach, Barragán and Terrados (2017) have identified 11 technologies that could be applied to inner cities: biomass, biodigestor biogas, sanitary landfill biogas, incineration, tidal, small wind, small hydroelectric, photovoltaic, solar thermal, bioethanol and geothermal technologies. Eight are useful for electricity production, as shown in Table 1. The particularity of these technologies is that they use the resources available in cities or that come from internal processes (urban waste or wastewater).

2.4 Selection of criteria

The selection of criteria is fundamental because decision makers evaluate the alternatives using these parameters. Twenty-two papers that applied multiple criteria were analysed. Fifty-nine subcriteria were identified and classified by their technical, economic, environmental and social aspects. An additional 37 research projects related to the eight technologies for electricity generation were reviewed, and 11 new subcriteria were thus obtained. Finally, to determine the subcriteria to be utilised, the following considerations were assumed.

- Subcriteria that are not influential with regard to REs are discarded.
- Subcriteria that were used in less than 20% of the analysed studies are discarded.
- The subcriteria can be measured both qualitatively and quantitatively.
- Subcriteria have been considered according to the frequency of use in the literature to balance the different dimensions involved.
- Subcriteria are chosen according to information availability.
- The number of criteria is limited because if there are many criteria, their weight values increase the difficulty of applying the method.

According to the previous conceptualisation, the subcriteria are set forth in Table 2. The qualitative subcriteria were determined using a bibliographic review. Thirty-three research papers and international organisation reports were identified that contained the required information. In most cases, the quantitative criteria were obtained by consulting local academic experts and public companies or through consultation. Some subcriteria are more suitable when they have higher values (e.g. efficiency), whereas others are more suitable at lower values (e.g. emissions); they must be maximised or minimised according to the objective(s) of the problem.

2.4.1 Technical subcriteria

Efficiency. Indicates electrical energy obtained after conversion. Table 3 shows a comparison of the analysed alternatives.

Primary energy resource availability. The criterion for primary energy availability required for a given technology. Not knowing the potential of a renewable source is a barrier;

Table 1. Resources for electricity production in cities

Technology	Alternative	Resources	Conversion
Biomass	a1	Forest urban waste	Combustion
Biogas	a2	Wastewater sludge	Anaerobic digestion
Biogas landfill	a3	Fraction of biodegradable urban waste and pruning waste	Combustion
Incineration	a4	Urban solid waste	Mechanical
Tidal	a5	Water	Mechanical
Small hydroelectric	a6	Water	Mechanical
Small wind	a7	Wind	Mechanical
Photovoltaic	a8	Solar radiation	Photoelectric effect

Table 2. Subcriteria for selecting electric energy production technologies

Criterion	Subcriterion		Unit	Type
Technical	c1	Efficiency	%	Quantitative
	c2	Availability of primary source		Qualitative
	c3	Technological maturity		Qualitative
	c4	Urban obstacles and availability of the area		Qualitative
	c5	Architecture intervention		Qualitative
Economic	c6	Initial investment	US$/kW	Quantitative
	c7	Cost of operation and maintenance	US$/kW	Quantitative
	c8	Cost of energy	US$/kWh	Quantitative
Environmental	c9	Global warming	Carbon dioxide: kg/TJ	Quantitative
	c10	Acidification	Sulfur dioxide: kg/TJ	Quantitative
	c11	Eutrophication	Nitrogen oxide: kg/TJ	Quantitative
Social	c12	Employment	Job-years/GW	Quantitative
	c13	Social acceptance		Qualitative
	c14	Compatibility with international, regional or local policies		Qualitative

Table 3. Efficiencies of electric energy production technologies

Alternative	Biomass	Biogas	Biogas landfill	Incineration	Tidal	Small hydroelectric	Small wind	Photovoltaic
Efficiency: %	25[a]	26[b]	33[b]	29[b]	90[c]	90[d]	20[e]	12[f]

[a]Panepinto *et al.* (2014)
[b]Gómez *et al.* (2010)
[c]Radtke *et al.* (2011)
[d]Xu *et al.* (2015)
[e]Bukala *et al.* (2015)
[f]Khan and Arsalan (2016)

Table 4. Maturity levels of electric energy production technologies

Alternative	Biomass	Biogas	Biogas landfill	Incineration	Tidal	Small hydroelectric	Small wind	Photovoltaic
Degree of maturity	3[a]	3[b]	3[c]	3[c]	3[d]	3[e]	2[f]	3[d]

[a]Roberts *et al.* (2015)
[b]Shen *et al.* (2015)
[c]de Souza *et al.* (2014)
[d]IDAE (2011)
[e]Gsänger and Pitteloud (2015)
[f]Xu *et al.* (2015)

extensive research must be undertaken to measure resource availability.

Technological maturity. A qualitative scale is considered: a value of 3 indicates commercial maturity, 2 indicates under-development and 1 indicates the research stage (see Table 4).

Urban obstacles and area requirement. Urban density plays an important role. High urban density often involves less space for infrastructure.

Architectural affectation. The intrusion of the infrastructures of energy generation within cities modifies the aesthetic appearance of the urban context.

2.4.2 Economic subcriteria

Investment cost. To determine the investment required, costs are extrapolated from one scale to another using Equation 5. In addition to technical maturity and depending on the intensity of development, costs normally decrease (IRENA, 2016).

$$5.\quad \frac{C_1}{C_2} = \left(\frac{S_1}{S_2}\right)^p$$

C_1 and C_2 are plant costs (US$), and S_1 and S_2 are the sizes of the plants (MW) (Danish Energy Agency and Energinet.dk, 2012; OECD, 2015). For electricity generation plants, a scale factor p of 0·75 was assigned. Table 5 presents the results if all plants are referenced to 1 MW.

Operational and maintenance costs. This criterion considers the investment required in operating the system (personal, products or services) and the costs required during its lifespan. This criterion is expressed in Table 6 by relating it to a percentage of the technology's investment cost.

Table 5. Costs of technologies, considering the scaling factor

Alternative	Reference plant: MW	Cost of reference plant: MUS$	Cost of 1 MW: US$/kW
Biomass	10·00	44·60	7931[a]
Biogas	10·00	44·60	7931[a]
Biogas landfill	5·00	8·96	2680[b]
Incineration	110·00	1232·00	36 272[b]
Tidal	1500·00	5221·50	21 663[c]
Small hydroelectric	3·10	15·89	6803[a]
Small wind	0·0095	0·06	2185[a]
Photovoltaic	0·90	2·01	2182[d]

[a]OECD (2015)
[b]Danish Energy Agency and Energinet.dk (2012)
[c]Poyry (2014)
[d]DWEA (2015)

Energy production costs. Levelised cost of electricity (LCOE) is calculated using Equation 6. A 1 kW base price was considered for the analysis, along with the corresponding operations and maintenance costs. A discount rate of 10%, which indicates high risk, is suggested by OECD (2015) over the lifetime. Table 6 presents the results and indicators used for the calculations.

$$6.\quad \mathrm{LCOE} = \frac{\sum_t [\mathrm{Inv}_t + \mathrm{O\&M}_t](1+r)^{-t}}{\sum_t [\mathrm{Elec}_t (1+r)^{-t}]}$$

Table 6. Cost of electrical energy production

	O&M		LCOE		
Alternative	% Inv	US$/kW	Lifetime: year	Work hours	US$/MWh
Biomass	3·3[a]	262	40[a]	7000[b]	153
Biogas	16[c]	1269	20[c]	8000[d]	275
Biogas landfill	7·4[a]	198	22[e]	8000[c]	63
Incineration	4·0[c]	1451	20[e]	8000[c]	713
Tidal	3·7[a]	802	20[a]	2450[f]	1365
Small hydroelectric	2[a]	136	70[g]	6132[h]	133
Small wind	3·2[a]	70	20[i]	1533[j]	213
Photovoltaic	1·2[a]	26	25[k]	1450[l]	183

[a]Connolly *et al*. (2016)
[b]OECD (2015)
[c]Gómez *et al*. (2010)
[d]de Souza *et al*. (2014)
[e]Danish Energy Agency and Energinet.dk (2012)
[f]Leite Neto *et al*. (2015)
[g]Xu *et al*. (2015)
[h]Fujiia *et al*. (2015)
[i]Karthikeya *et al*. (2016)
[j]DWEA (2015)
[k]Byrne *et al*. (2016)
[l]IDAE (2011)

where LCOE is the cost of electrical energy production during the lifespan (US$/kWh); Inv is the investment in a year (including interest during construction and all auxiliary elements and electrical infrastructure) (US$/kWh); O&M is the operation and maintenance cost in a year t (US$/kWh); r is the discount rate; Elec is the electricity generated in year t (kWh); and t is the plant lifetime operation (years).

2.4.3 Environmental subcriteria

Global warming. Considering greenhouse gas emissions, carbon dioxide (CO_2) is used as an indicator of fossil fuel burning.

Acidification. Sulfur dioxide (SO_2) emissions into the atmosphere produce acid rain, causing diseases in ecosystems and affecting people's health.

Eutrophication. Fossil fuels produce nitrogen oxide (NO_x) emissions. The main environmental problem is the eutrophication produced by the excess of nutrients deposited in water or on land.

The values used for the proposed environmental criteria are shown in Table 7. As far as the technology life cycle is considered, the emission factors are related to the energy used to manufacture the components.

2.4.4 Social subcriteria

Employment creation. Different indicators calculate the required manpower in concordance with energy production (Wei *et al*., 2010), mainly for the stages of (*a*) construction, installation and manufacturing (CIM) and (*b*) operations and maintenance (OM). The first indicates the number of workers involved in the initial stage of the technology. The second expresses the number of jobs required for lifetime operations and maintenance. The total of job-years/GWh was calculated using Equation 7, and the results are presented in Table 8.

Table 7. Environmental subcriteria

Alternative	Carbon dioxide: kg/TJ	Sulfur dioxide: kg/TJ	Nitrogen oxide: kg/TJ
Biomass	8611[a]	32[b]	367[a]
Biogas	3056[a]	201[a]	160[a]
Biogas landfill	305 555[c]	1583[a]	756[d]
Incineration	61 111[c]	444[e]	—
Tidal	3473[f]	74[g]	14[g]
Small hydroelectric	2500[b]	7[h]	12[a]
Small wind	2222[b]	13[g]	9[a]
Photovoltaic	36 806[b]	83[g]	94[a]

[a]Pehnt (2006)
[b]Akella *et al*. (2009)
[c]Nixon *et al*. (2013)
[d]Dawoud *et al*. (2012)
[e]Jeswani and Azapagic (2016)
[f]Masanet *et al*. (2013)
[g]Masanet *et al*. (2013)
[h]UtA (2003)

Table 8. Jobs generated by electricity production technologies

Alternative	CIM: job-years/MW	OM: jobs/MW	Total job: job-years/GWh
Biomass	4·29[a]	1·53	0·23
Biogas	25·00[b]	6·00	0·91
Biogas landfill	3·71[a]	2·28	0·30
Incineration	101·16[c]	1·41	0·81
Tidal	20·4[d]	0·60	0·66
Small hydroelectric	5·71[a]	1·14	0·20
Small wind	10·10[a]	0·40	0·59
Photovoltaic	37·00[a]	1·00	1·71

[a]Wei *et al*. (2010)
[b]Moreno and López (2008)
[c]IDAE and ISTAS (2011)
[d]Rutovitz *et al*. (2015)

7. $$\text{Total jobs} = \left[\frac{\text{CIM}}{t} + \text{OM}\right] \times \frac{1000}{T}$$

where t is the lifespan of the RE, in years; T is the number of hours the technology operates in 1 year; CIM is the number of people who were used to build an MW reference infrastructure, in job-years/MW; OM is the number of jobs required for the operation and maintenance of the installation, in jobs/MW.

Social acceptance. This subcriterion considers whether citizens agree with the presence of renewable technologies within the city.

Public policies compatibility. The growth of RE in national contexts is normally the result of political support for the large-scale development of these technologies.

2.4.5 Qualitative criteria obtention

Due to the lack of information when choosing some of the subcriteria, a qualitative assessment was chosen. Local experts on energy situations and in RE were contacted. After the professionals and experts in the field were identified, they were introduced to the aspects of the research. Those who agreed to participate were given a questionnaire (Figure 2 shows part of the survey that was sent), in which they were asked to evaluate their theoretical or experimental experience, individual knowledge of the specialised literature and intuition. After analysing the expertise of each participant, an answer matrix was obtained for each subcriterion. The evaluation of each criterion was performed using a Likert scale (1–5). The definitive values were the averages of the ratings. Cronbach's alpha coefficient (α) was used to guarantee the reliability of the results. For this study, a coefficient of 0·65 was considered to be acceptable for validating the stated objectives. Once the reliability was guaranteed, the average values obtained from the answers were used for the corresponding criteria in the decision matrix.

2.5 Decision matrix design

Numeric values (qualitative and quantitative) are assigned to each a_i alternative, according to the proposed subcriteria. In the decision matrix, the alternatives and their valuations according to the established criteria are presented in every row (Wang *et al.*, 2009).

2.6 Assigning weight values

The easiest way to assign weights is to insist that each criterion starts on the same level (equal weights – EW). However, each criterion and subcriterion produce different impacts according to the alternatives, which is why they are assigned weights, w_j, that indicate their relative importance (Wang *et al.*, 2009). The direct rating method (DRM) was used to determine the weights. If there are k subcriteria, the sum of the weights will equal 1.

To obtain the weight values, a Google survey was distributed to the 118 the experts and public and private employees; 58 forms were filled out. Figure 3 shows a screenshot of the questionnaire. Since the goals for this approach also include validating its extrapolability to different cities, the survey was conducted in several countries (primarily in Ecuador, 29%;

De las siguientes tecnologías, cuál considera que **PODRíA IMPLEMENTARSE EN LA CIUDAD DE CUENCA.** Califique en escala de l a 5. 5 más impacto, l menos impacto. Dos o más tecnologías pueden tener la misma valoración.

Subsistema	Sustituye al portador energético	Calificación
Bioetanol	Combustible líquido	
Biomasa	Electricidad	
Biogás (biodigestores)	Electricidad o combustible líquido	
Biagás (rellenos sanitarios)	Electricidad	
Incineración Co-incineración	Electricidad Combustible líquido o gaseoso	
Mareomotriz	Electricidad	
Pequeña Eólica	Electricidad	
Geotermia	Electricidad Combustible liquido o gaseoso	
Pequeña hidroeléctrica	Electricidad	
Fotovoltaico en terrazas o fachadas	Electricidad	
Solar térmica (agua caliente sanitaria)	Electricidad Combustible liquido o gaseoso	

Figure 2. Survey sent to local experts

Figure 3. Part of the survey submitted using Google forms

Table 9. Subcriteria weights

	c1	c2	c3	c4	c5	c6	c7	c8	c9	c10	c11	c12	c13	c14
EW: %	7·14	7·14	7·14	7·14	7·14	7·14	7·14	7·14	7·14	7·14	7·14	7·14	7·14	7·14
DRM: %	7·7	8·6	7·2	6·8	5·7	8·3	7·5	8·4	7	6·3	6·1	6·2	7	7·2
OR: %	10	23	6	3	1	12	8	16	4	2	1	2	5	7

cj, corresponds to the subcriteria detailed in Table 2; EW, equal weights; DRW, direct rating method; OR, ordinal ranking

Spain, 22%; Argentina, 9%; Honduras, 7%; Uruguay, 7%; and Bolivia, 5%) between November and December 2016. Of the opinions, 45% belonged to the academic field, followed by 31, 14 and 10% for public, private and other institutions, respectively. Each subcriterion was evaluated according to the Likert scale (1–10). Cronbach's alpha coefficient was used to measure the reliability of the survey; the result was a 0·88 index, which indicates high reliability.

The weight of each subcriterion, w_j, is established by obtaining the average of the individual valuations and is then normalised by dividing each medium value by the sum of the medium values.

To undertake a comparative analysis, the ordinal ranking (OR) method was used. This method enables the criteria to be ordered according to their importance. If k criteria are organised in ascending order, the expected values, which correspond to the weights, are given by Equation 8.

8.
$$\begin{aligned} w_1 &= \frac{1}{k^2} \\ w_2 &= \frac{1}{k^2}+\frac{1}{k(k-1)} \\ w_{k-1} &= \frac{1}{k^2}+\frac{1}{k(k-1)}+\ldots+\frac{1}{k2} \\ w_k &= \frac{1}{k^2}+\frac{1}{k(k-1)}+\ldots+\frac{1}{k2}+\frac{1}{k1} \end{aligned}$$

The weight valuation results obtained by applying the previous three approaches are shown in Table 9.

3. Application of the methodology to Cuenca City

The qualitative criteria (except for c3) were obtained by giving a survey to 30 professionals, 13 of whom fulfilled the previously established requirements. Of the respondents, 54% were in the academic sector, 38% in the public sector and the remainder in the private sector. The values of the quantitative and qualitative criteria that were used are shown in the decision matrix in Table 10. The a5 (tidal) alternative was not considered for Cuenca because the city is located in a mountainous area distant from oceans or lakes.

3.1 Prioritisation and decision making

The comparison between the alternatives determined a partial and then a complete ranking. The results were compared using different weights of the subcriteria. The net flows are presented in Figure 4. The net flows corresponding to hydro, photovoltaic and landfill gas technologies were preferred in all cases.

To improve the percentage of information in the Gaia plane, the subcriteria were grouped into the following criteria: technical, economic, environmental and social. Figure 5 presents the Gaia diagram, which shows additional information on the alternatives according to the net flows. Alternatives a3 (biogas landfill) and a8 (photovoltaic) were preferred in the technical and social dimensions, whereas a6 (hydroelectric) and a7 (wind) were preferred in the social and economic dimensions. The a1 (biomass), a2 (biogas) and a4 (incineration) alternatives were not preferred for any dimension. In this case, the decision axes for the group of economic criteria were a8, a6 and a3, which were better ranked.

4. Results and discussion

The Gaia plane analysis evaluations for the different cases are shown in Table 11. Regarding the technical dimension, the landfill gas and photovoltaic technologies were most preferred, and incineration and wind were the least preferred. For the economic criteria, the photovoltaic, hydroelectric and landfill gas technologies were better ranked, and incineration and biogas biodigestors were the least preferred. In the environmental dimension, wind, hydroelectricity and biomass technologies were preferred, whereas landfill gas and incineration were the worst ranked. Finally, with respect to the social criteria, electrical energy from landfill gas, solar photovoltaic panels, and hydroelectric would be compatible with local policies and accepted by the community.

As noted, in the overall analysis, the most suitable electricity generation technologies for implementation in the city of Cuenca are photovoltaic, hydroelectric and landfill gas technologies. These results coincide with the resources available in the city and with the completion of projects that are underway.

From a quick analysis of photovoltaic potential on roofs in Cuenca, the total city area occupies 73·01 km^2 and has

Table 10. Decision matrix

Alternative	c1[a]	c2	c3	c4	c5	c6	c7	c8	c9	c10	c11	c12	c13	c14
	%					US$/kW	US$/kW	US$/MWh	kg carbon dioxide/TJ	kg sulfur dioxide /TJ	kg nitrogen oxide /TJ	job-years/ GWh		
	M[b]	M	M	M	m[c]	m	m	m	m	m	m	M	M	M
Biomass	25	2·18	3	2·64	2·64	7931	262	153	8611	32	367	0·23	2·45	3·00
Biogas	26	2·55	3	2·55	2·18	7931	1269	275	3056	201	160	0·91	2·45	2·82
Biogas landfill	33	3·27	3	3·45	2·36	2680	198	63	305 555	1583	756	0·30	3·36	3·27
Incineration	29	2·18	3	2·45	2·91	36 272	1451	713	61 111	444	—	0·81	2·00	2·27
Small hydroelectric	90	3·55	3	3·27	3·55	6803	136	133	2500	7	12	0·20	2·45	3·82
Small wind	20	2·64	2	2·91	3·55	2185	70	213	2222	13	9	0·59	3·27	2·73
Photovoltaic	12	4·00	3	3·00	3·27	2182	26	183	36 806	83	94	1·71	3·82	3·18
α	—	0·70	—	0·65	0·65	—	—	—	—	—	—	—	0·83	0·88

[a] *cj*, corresponds to the subcriteria detailed in Table 2
[b] *M*, indicates that the criterion is maximised
[c] *m*, indicates that the criterion is minimised

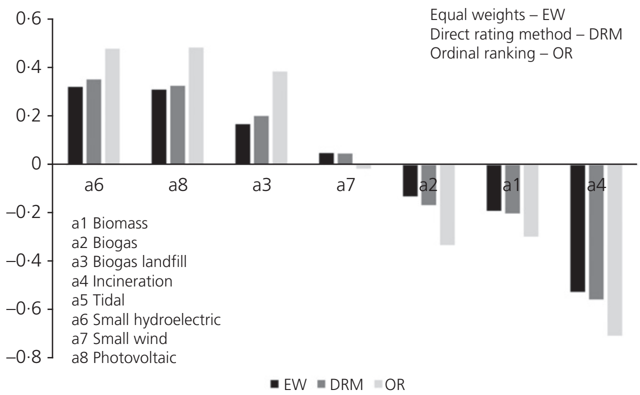

Figure 4. Net flows of the proposed technological alternatives

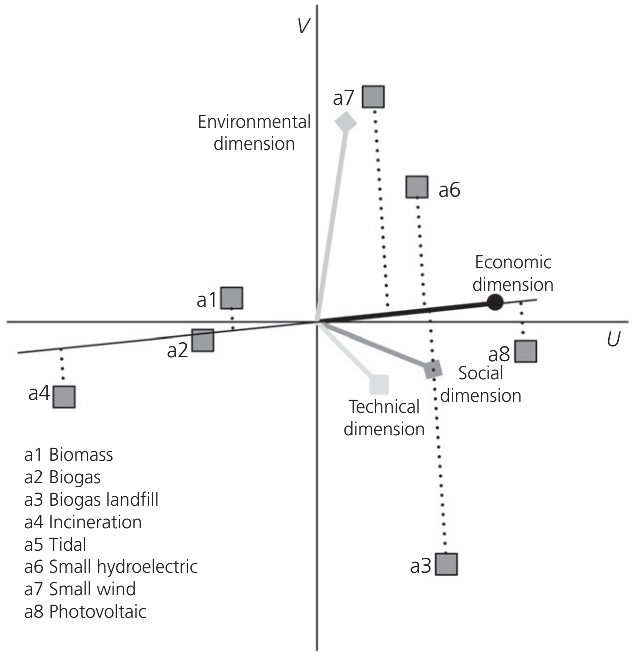

Figure 5. Gaia diagram, DRM case

1615 kWh/m^2 per year of global horizontal incident solar radiation. Considering very low efficiencies of 12% for photovoltaic panels and 95% for regulators and using an average electricity consumption of 1000 kWh/inhabitant, 2·46% surface occupancy would be required to cover the city's total demand. Considering roof availability and solar paths at the high altitude, the roof surfaces largely oversupply the area required. Nevertheless, a smart grid scenario is required to control hourly production mismatches, but due to the absence of seasons, solar radiation and energy demands are very stable all year.

Table 11. Ranking of alternatives for each dimension of the analysis

	Technical			Economic			Environmental			Social		
Order	EW	DRW	OR	EW	DRW	OR	EW	DRW	OR	EW	DRW	OR
1	a3	a3	a3	a8	a8	a8	a7	a7	a7	a3	a3	a3
2	a8	a8	a8	a6	a6	a6	a6	a6	a6	a8	a8	a8
3	a2	a6	a6	a3	a3	a3	a1	a1	a1	a6	a6	a6
4	a1	a2	a7	a7	a7	a7	a8	a8	a2	a7	a7	a7
5	a6	a1	a1	a1	a1	a1	a2	a2	a8	a1	a1	a1
6	a4	a7	a2	a2	a2	a2	a4	a4	a4	a2	a2	a2
7	a7	a4	a4	a4	a4	a4	a3	a3	a3	a4	a4	a4

a*j*, corresponds to the alternatives detailed in Table 1; EW, equal weights; DRW, direct rating method; OR, ordinal ranking

Likewise, a 2 MW power plant that uses biogas from the city's sanitary landfill is under construction; the plant could supply between 1 and 2% of the urban area's energy demand. Regarding hydropower resources, four rivers pass through the city where small hydroelectric power plants could be installed. Ecuador has great water resources and experience in the construction and operation of hydroelectric power plants. Although the results indicate the attractiveness of that technology in these plants' installations, the river sources have not been evaluated. Preliminary studies indicate that at least one 6 MW power plant can be built that would take advantage of the flow of one of the rivers.

Wind technology is mainly applicable in rural environments and at commercial scales. However, for its mass deployment, it requires more technological progress for use in urban environments (Millward-Hopkins *et al.*, 2013). In the future, it is expected that vertical axis technology will be relevant for cities. Regarding power from biomass and biodigestor gas, despite being mature technologies, the qualitative valuation indicated scepticism for acceptance at the local level, especially when there are no local projects and the potential of the city's resource is as yet unknown. Since urban wastes have high moisture contents, incineration is not considered to be an appropriate technology at a local level.

In Ecuador, the actual electricity production and distribution cost is US$0·09/kWh and is reduced to US$0·04/kWh after public subsidy. However, the calculated costs of electricity for photovoltaic, landfill and hydroelectric technologies would be US$0·18, US$0·06 and US$0·13/kWh. As a consequence, adequate legislation is necessary for properly targeted subsidies that allow micro-generation sales to the grid and credit policies that allow cost apportionment over the life of the installation. The applicability of renewable technologies should be considered during the urban planning stage. Although current urban infrastructures and buildings do not consider these facilities, future guidelines for medium- and long-term RE implantation are possible. Therefore, urban energy planning must include urban sources as energy alternatives.

Consulting experts have solved the issue of low-data availability for some criteria in Cuenca. To validate the questionnaire, the participants' experiences were analysed. From an initial number of 30, it was concluded that 13 had appropriate profiles and the required expertise. This is reflected in the reliability given by the Cronbach coefficient. The results could be improved by conducting a second round of interviews that would present some information from the first survey as a starting point.

The international survey given to 58 professionals to define the preponderance of the subcriteria provided interesting results. Without considering a specific city, it is clear that applications of the technologies depend on the existence of renewable resources. Conducting research beforehand is the only way that allows evaluation of these technologies. However, for developing countries, it is preferable to focus the analysis on those technologies that are considered more appropriate for implementation. Investment and energy costs are other decisive factors, and if these technologies are not financially attractive to implement, it is very difficult to establish them, especially when REs are considered to be small distributed sources. Citizens will assume that it is preferable to pay an electric fee rather than paying for their own installations and maintaining them, with regard to energy received from the grid.

The specialists considered aesthetic and architectural aspects and space availability to be less influential. Although some technologies do not necessarily require built-up areas and can even be installed in industrial zones (biomass, biogas, incineration and tidal), it must be considered that others may affect architectural aspects or require additional space (photovoltaic or wind).

Considering social factors such as job creation, citizen acceptance and compatibility with local policies, low social opposition was observed. Probably because citizens consider these technologies to be attractive and limitations such as high prices are solved, strong social support is expected at governmental or public levels. Although employment opportunities are also an attractive consequence, in general, that factor is among the least valued, possibly because this sector is not considered to have a significant influence on employment rates, especially in countries that are not manufacturers but importers of RE technologies.

The environmental aspects are the least influential factors. This may be because although electricity is an important energy source, at the urban level, the consumption of fossil fuels is considered to be the main cause of environmental problems. Citizens do not see the environmental impacts caused by the exploitation of resources in the countryside for the production of electricity. They are not aware of large power stations or the transmission lines required to transport electricity.

5. Conclusions

The objective of RE production in urban areas is to reduce energy imports from external sources, which requires analyses that go beyond the economic aspects. Proper medium- or long-term technologies must be determined so that they can be promoted in specific cities. Due to the lack of certainty in the results and a series of dilemmas that can occur when choosing RE sources, decision-making techniques must be developed.

A multiple-criteria methodology has been established for cities that had previously been used at national and regional levels, and this change in scale is the proposal and main contribution of this research. Comprehensive energy planning that considers distributed renewable technologies should also consider the participation of local municipalities, which can issue proper local laws more quickly and easily. When evaluating the preponderance of the weight values of the 14 subcriteria, it was possible to identify conditions of greatest interest for the inclusion of renewables in the urban energy planning stage. The reliability of the survey supplied to international experts also ensures that these data could be extrapolated.

The main finding and concrete result of this research in Cuenca is the identification of three technologies: photovoltaic, mini-hydro and gas landfill. The results reflect the logical consequences of local and particular conditions, such as high and stable solar radiation, the presence of rivers crossing the city and the adequate management of waste that can be used for energy production. The main barrier was the limited number of experts to evaluate the qualitative criteria, but the results obtained were acceptable. To improve reliability, the survey could be extended to national experts and the Delphi methodology could be used, with more than one round of participation.

Actual urban energy matrices are complex and mainly use energy based on fossil fuels (90% in Cuenca). Nevertheless, the three technologies show an interesting potential to complement each other, considering the intermittence of solar radiation, that mini-hydropower is more stable over time, and that gas landfills could provide supplies when the power network experiences shortages. To clean the environment and balance the network, electric vehicles are an option to alleviate the high demands of fossil fuels. The research should be extended to energy sources such as solar thermal energy for heating water or biofuels and to simulate the real potentials of each technology, without discarding those not selected as complementary alternatives.

This methodology could be useful for other intermediate cities, especially in developing countries. Medium-sized and small cities are more suitable for establishing planning guidelines that can reduce material and energy inputs. Under this approach, the reduction of energy coming from outside will allow these cities to be planned following a circular urban metabolic model.

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