

Review

# The Role of Renewable Energy in the Promotion of Circular Urban Metabolism

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Received: 28 October 2017; Accepted: 12 December 2017; Published: 15 December 2017

**Abstract:** Cities are human creations requiring large amounts of materials and energy. Constant consumption of resources exerts pressure on the environment not only due to its exploitation, but also because once processed, the resources produce waste, emissions or effluents. Cities are responsible for more than three quarters of the emissions of greenhouse gases. It is anticipated that the urban population will increase by up to 80% by the mid-21st century, which will make the current energy model unsustainable, as it is based on the intensive use of fossil resources. A change in urban planning is required to meet the energy requirements of cities. Several studies mention that renewable energy must be used in cities, but they do not identify the resources and technologies that can be used to promote circular urban metabolism. A review of the literature establishes that there are eleven renewable technologies with different degrees of maturity that could reduce the import of energy resources, which would contribute to changing the metabolic linear model into a circular model. However, the applicability of the different possibilities is conditional upon the availability of resources, costs, policies and community acceptance.

**Keywords:** renewable energy; urban metabolism; circular economy

## 1. Introduction

Cities are currently home to more than 53% of the human population and are growing; their existence depends on energy development, and their energy demands are concentrated in buildings, transport, industrial processes or other types of infrastructure [1,2]. The residents of cities import a large amount of materials that are transformed through processes that cause relative or critical impacts at the global or regional scale [3]. In urban areas, between 71% and 86% of greenhouse gas emissions are the result of energy demand, surpassing world energy needs by three-quarters [1,2,4]. Future expectations estimate that by the mid-twenty-first century, more than 80% of the population will reside in urban areas, and energy and material requirements will increase [5].

Cities occupy less than 3% of the surface of the Earth [6], which implies a high population concentration [7] and entails an enormous amount of economic activity and material accumulation, requiring large amounts of energy and materials [6,8]. This demand has a great impact on the environment [9,10]. The high concentration of housing generally leads to poor quality of life due to side effects such as noise, reduction of privacy, pollution or traffic congestion [11].

However, there are unequal subsistence conditions per capita, since 10% of the population consumes 40% of the energy and 27% of the materials [7]. According to the current trends, this inequality in energy consumption is not expected to change radically.

The discovery of new oil fields and the improvement in energy efficiency has postponed a reform at the global level that would limit the use of non-renewable resources, despite the fact that the currently available technology can lead to an energy revolution. Without an energy revolution, the planning of cities will face a new energy era subject to energy and fossil resource shortages [12]. Global urbanization trends demand revisions of urban energy policies [13,14].

Non-renewable energy sources have expiration dates, and available renewables have obstacles that prevent their full use at early stages. Georgescu-Roegen [15] argues that available energy must also be accessible, even when the energy source is infinite (as with solar or wind), there are limitations. These limitations have gradually been resolved over the years, so it is currently feasible to take advantage of renewables in urban environments.

The UN General Assembly adopted the 2030 Agenda for Sustainable Development in September 2015. Member countries committed to fulfil targets related to energy use, the creation of infrastructure and city maintenance under a sustainable development approach. This commitment seeks to make cities more resilient with regard to climate change, simultaneously promoting the economy and decreasing poverty [16]. At the United Nations Conference on Housing and Sustainable Urban Development (Habitat III), which occurred in October 2016 in the city of Quito, Ecuador, the need to promote energy efficiency and the use of non-polluting energy sources at the urban level was proposed [17].

Energy self-sufficiency achieved through the use of renewable energy (RE) in cities is fully aligned with these requirements. Moreover, the high density of the urban population offers opportunities to achieve economies of scale and allows the promotion of plans focused on efficient energy management, transportation networks and sewage or waste management [11]. Several investigations have proposed alternatives. Despite the lack of practicality in the short-term, these alternatives need to be analyzed, especially in cities in which planners do not consider consumption and the decrease in material resources or energy [6,12].

Cities rely on varied residual energy or renewable resources that can be incorporated into energy matrices. Although the use of renewable resources may have environmental merits, it is difficult for some renewable technologies to gain an important share of the urban energy matrix [18]. First, the reformulation of energy policies is required, allowing modification of the community demand [6], thus promoting awareness and changes in consumption behavior, market dynamics and political forces.

The concept that allows the analysis of the supply of energy resources is called urban metabolism (UM) and is defined as “the total sum of technical and socio-economic processes that occur in cities to manage growth, energy production and disposal” [19]. Given the pressure exerted by cities on the environment, it is proposed that cities should not maintain a linear metabolism but should take advantage of and maximize the use of both inputs and outputs. According to Agudelo-Vera et al. [9], cities can be seen as reservoirs and producers of secondary resources. The ideal situation for cities would be to coexist within the natural environment. This approach has traditionally served to establish flows of urban materials and energy. Despite the establishment of a strong circular metabolic process, studies have rarely focused on energy self-sufficiency through renewables.

There are several studies that consider the applications of UM as a tool to promote sustainability, whereas other studies analyze the application of renewable technologies in cities. Following these principles, the Hammarby Model proposes to reduce energy flows, particularly those of secondary energy, by using renewable energy [20]. The SoURCE project (Sustainable Urban Cells) determines the energy balance between the provision of renewable energy sources and energy consumption [21] and establishes the possibility of maintaining a close balance between the energy requirements and renewable energy in a community. The concept of the energy center described by Orehounig et al. [22] analyses the relationship of the input and output flow and energy demands in a village, as well as the types of energy required and their sources.

Through a literature review, this article proposes the integration of renewable energies in cities to reduce urban energy dependence from the perspective of circular energy metabolism. To achieve this

integration, we start with an analysis of UM principles and review the studies evaluating the potential energy contribution of renewable energy sources in cities.

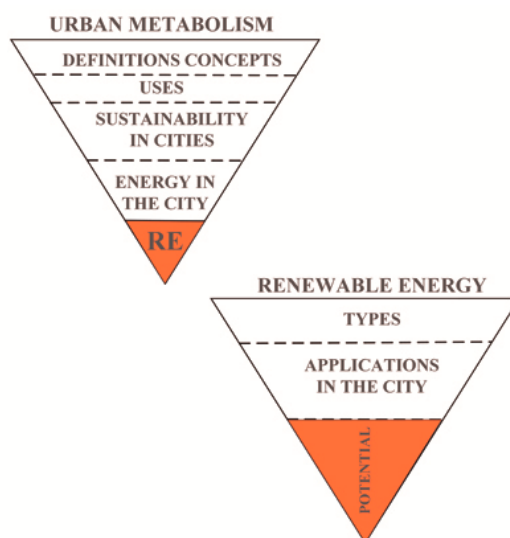
## 2. Materials and Methods

UM is a model that quantifies processes and allows the measurement of four main cycles or flows: Water, materials, energy and nutrients [19,23]. The models used have evolved from the black-box process through a cyclical process into models that study material internal flows or energy inside cities [24]. These techniques are aimed at developing mechanisms to allow cities to be designed to simulate natural ecosystems to avoid exerting excessive pressure upon the environment [25].

According to the proposal by Yan Zhang et al. [24] (see Equation (1)), the flows of urban energy (U) are given by summing the renewable energy (RE), the non-renewable energy (N) and imports (IMP):

$$U = RE + N + IMP \quad (1)$$

If the U requirement is kept (i.e., without adopting energy efficiency measures), then it is necessary to increase renewable energy use to reduce the use of non-renewable energy and imports. A literature search has been conducted to identify (i) a UM that includes general concepts, reviews, assessment methodologies and suggests the use of renewable energy and (ii) research related to renewable energy use, including technical, economic, environmental and social aspects. In addition, renewable technologies able to supply part of the urban demand with resources that have or have come from the cities have also been identified. Figure 1 outlines the process that is used to relate RE to UM.



**Figure 1.** Process that is used to relate RE to urban metabolism (UM).

## 3. Urban Metabolism

In 1965, Abel Wolman [26] analyzed and quantified the input and output streams to a city of a million inhabitants, initiating the use of the UM concept. Wolman defined UM as “... all materials and raw materials needed to sustain city inhabitants”. In 2007, Christopher Kennedy et al. [19] defined UM as “... the total sum of technical and socio-economic processes that occur in cities conducting to growth, production of energy and waste disposal”.

Kennedy [27] and Golubiewski [28] discuss whether the city should be considered an ecosystem or an organism. Kennedy [27], from a pragmatic perspective, considers that cities are not living organisms in the biological sense, although they grow, produce or transform energy and eliminate waste. He argues that UM is essential for understanding the connection between ecology and

economics. In the same sense, he concludes that the terms of metabolism can be managed as an urban ecosystem, establishing that the city is an ecosystem.

UM compares cities to a single ecosystem or to the sum of ecosystems [23]. From this perspective, cities could be considered under-developed ecosystems [10] highly dependent on external resources. Humans exchange the materials and energy required to eat, work, live, travel, and communicate with those outside the city's limits [29]. This ecosystem is interconnected with entities outside of it, so any decision that modifies consumption patterns directly influences resource availability [30].

The city must have the ability to be adaptive. Cities require data to weigh options to meet needs, ensuring alternatives in the case of a shortage of external resources [9,31]. This concept can only be validated if resources are measured to serve as source substitutes for defined applications.

The city–environment relationship is complicated by inefficient consumption of energy and materials [24]. The resources from its surroundings require processing to meet consumption conditions [31]. Part of the inputs processed in goods or services are then disposed like waste to the environment [32]. Additionally, large amounts of wastewater, solid waste, construction waste or other wastes are disposed outside urban areas while others remain inside [9].

UM conceives cities as interactive ecosystems, therefore economic, social or ecological rules apply as processes in an interaction with the external environment [33]. Unlike linear metabolism, where the required matter and energy comes from outside urban boundaries and is largely discarded outside of them (non-related inputs and outputs) [34], in circular metabolism, the resources are local, reducing external demand; therefore, the inputs and outputs of the city are connected (from the cradle to the cradle) [5]. This requires both the use of disruptive technologies (renewable energy, energy efficiency) as well as recycling and reuse for different urban material flows [9].

This linearity is manifested in most urban systems [35] by having as inputs extensive quantities of materials (energy, food or raw materials) that have outputs as goods, services and waste. From this perspective, there are two issues: (i) the high need for resources, which compromises provision sources, and (ii) massive waste disposal, causing pollution [9].

While the cycle is not closed—inputs, transformation, and uses—the metabolism will not be complete if there is no adequate disposal of waste [36]. The city is a vulnerable anthropogenic structure, not self-sufficient and incapable of self-detoxication [34], with external dependency [9]. Considering the previous arguments and following the proposal by Yan Zhang [25], an urban model is proposed whose energy management and inputs are sustainable and integrated into the life cycle and whose natural resources, recycled and reused materials [37] and optimized energy management, are managed through technological advancement, which makes it feasible.

In the study by Huang and Hsu [36], it is considered necessary to use results from UM studies to generate policies because the concept of traditional urban planning has been to consider, to a greater extent, visually pleasing spaces, orderly occupation, profitability, accessibility and agile transport rather than to promote environmentally friendly cities.

#### *Methods for Assessing Urban Metabolism*

The modelling of a city through the concept of metabolism is used for information regarding: energy, energy efficiency, recycling of materials, and waste management. In addition, the model allows quantification of both inputs and outputs or storage of water, energy, nutrients, materials and waste produced [25,37].

For UM studies, two general types of methodologies are used: those based on the inventory of inputs and outputs (materials and energy), and those that use biophysical indicators that allow the representation of the resources and energy efficiency in terms of energy and exergy [23,33,37]. In Table 1, several studies are presented that include inventories, balances, flows, indicators, comparisons between cities, efficiency assessments, and resource qualities.

**Table 1.** Different studies applying urban metabolism principles.

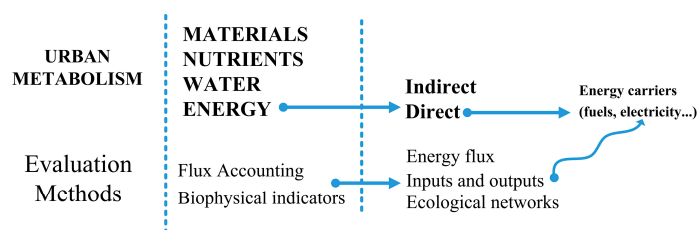
Schools <sup>a</sup>	Assesses <sup>b</sup>	Obtains <sup>c</sup>	Case Study	Author
Flow Accounting	Ma	In	Munich	[38]
		Inv, Fl, Ba, Be	Lisbon	[39]
	En	Ba, In,	Toronto	[31]
		Fl, Be, In	Singapore, Hong Kong	[40]
	Ma	Fl, Be	Typical American city, Brussels, Sydney, Tokyo, Hong Kong, Vienna, London, Cape Town	[19]
	En	Inv, Fl, Ba, Be	Los Angeles	[3]
		Inv, Ba, Be, In	Paris	[11,41]
		Inv, Fl, Ba, Be	Curitiba	[42]
		Inv, Fl, Ba, In	Bogota	[43]
Biophysical Indicators	Em	Inv, Fl, Ba, In	Taipei	[36]
		Inv, Fl, Ba, In	Taipei	[29]
		Ba, Be, In	Beijing, Shanghai, Tianjin, Chongqing	[32]
		Inv, Fl, Ba, Be	Beijing	[24]
	Ex	Inv, Rq, Ef	Kerkrade	[35]
		Inv, Rq, Ef	Wageningen	[9]

<sup>a</sup> [23,33,37]. <sup>b</sup> Materials (Ma), energy (En), emergy (Em), exergy (Ex). <sup>c</sup> Inventory of Resources (Inv), balance of inputs and outputs (Ba), annual flows (Fl), benchmarking (Be), indicators (In), resource quality (Rq), resource efficiency (Ef).

Figure 2 presents methods to assess power according to Chen and Chen [44]:

- Energy flows: allows monitoring the consumption of direct energy. Related energy is imported and exported depending on the fuel used [44–46].
- Inputs and outputs: allows evaluation of the direct and indirect energy between two productive sectors [25,47].
- Ecological networks: allows assessment of the direct and indirect energy between several productive sectors [25,33].

Unlike UM, which evaluates inputs and outputs of materials, energy has a behavior that differs because it is not reversible. Energy allows the processing of materials, and although energy can be stored in a general way, it is dissipated, reflecting its non-reversible nature [47]. An analysis of the internal energy relationships in a community must consider both direct energy and indirect energy. The first type is understood as the income from energy coming from electricity and fossil fuels, while indirect energy is embedded in the products [2,48]. For this work, renewable energies are identified as those able to replace direct energy or energy carriers.

**Figure 2.** Methods to assess the contribution of the RE in a city.

In the report by Grubler et al. [2], two types of energy accounting methods (based on physical flows or oriented economic flows) are established. Within the methods based on flows are the ‘final energy’ method, and ‘regional energy metabolism’ method. These methods use physical data, but the second method is used for a geographic region (in this case, boundary of the urban area).

#### 4. Energy in the Cities

The energy sector is strategic. On the one hand, the energy sector allows the maintenance and improvement of the conditions of life and on the other hand, the energy sector is a basic requirement for social development [49]. As in the case of ecosystems, in an open system like those in the cities, energy is essential for growth and maintenance [40]. Haberl [45] analyses the transformations of energy from a society based on hunting and gathering to an industrial society, passing through the agricultural society. Based on empirical estimates, he suggests that different “*modes of subsistence*” are closely related to the demand of energy, and in turn, the increase per capita energy is linked with sustainability issues.

The Industrial Revolution allowed the advancement of science and a dizzying rate of urban growth related to intensive use of energy supported by the exploitation of fossil resources [23]. For over two hundred years, the urban energy model has been based on the use of fossil fuels, first coal, which made industrial development possible, and then oil, which has facilitated urban growth [29]. However, the “the fossil fuels era” will be completed in the next 100–200 years, not only as an environmental requirement but also because of the physical limitation of the resource [34].

Societies that are dependent on the import of these resources are vulnerable because they have less control over their economy [6]. In addition, the resilience of such a society to external events is limited by its dependence on external resources. Paez [12] analyses the situation of cities in Mexico and concludes that they are not prepared to make the transition to alternate sources of energy as oil production slows and the cost of energy becomes more expensive. According to this analysis, the lack of preparation is due to a lack of laws, policies, plans, programs and human resources that makes it impossible to develop a post-oil energy agenda.

##### 4.1. Renewable Energy in the Cities

Self-sufficiency through renewable sources, such as solar photovoltaic, solar thermal or energy recovery from waste, can be an alternative to promote a closed cycle of energy in cities [19], to the extent that it is replaced by technologies that do not require fossil resources. Knowing the renewable potential that can exist within a city is a necessary step for their promotion, in front of the impacts associated with the extraction of fossil resources or financial risks due to the uncertainty of their future prices, and the environmental impact caused by their exploitation, transport and transformation. A self-sufficient city requires, in principle, a full knowledge of the resources it possesses, which can be a drawback since the majority of cities do not know about their potential resources [10].

One of the human challenges is to design cities based on urban metabolic processes [33]. With respect to energy, Chrysoulakis [44] adds that this requires maximizing and optimizing efficiency in buildings as well as extending the participation of renewables. Hassan [46] concluded that the key to achieving urban sustainability is reaching reduction of energy consumption by its efficient use or by renewable energy integration.

In this study, renewable technologies that can be applied in inner cities that will allow a relevant supply are identified. As a reference, the classification of the Institute for Diversification and Saving of Energy in Spain (Instituto para la Diversificación y Ahorro de la Energía, IDAE for its acronym in Spanish) is considered [47]. In Table 2, 11 sectors and 22 renewable energy systems are set. In each case, we identified potential uses of technologies within the city. The systems chosen were those with resources available within the city (biomass, solar, wind and geothermal) or starting from the city (waste or wastewater). The energy or materials that come from the outside are not considered because the focus is on urban circular energy metabolism. Therefore, biofuels that require raw material from



outside or thermoelectric solar devices are disregarded. In the case of hydroelectric power and tidal power, even when there are experiences of its implementation in urban areas, their use would be limited to a few cities with the appropriate conditions.

**Table 2.** Classification of renewable energies according to IDAE.

Sector	System	For urban Integration
Biofuels	Bioethanol	Yes
	Biodiesel	No
Biomass	Gasification	No
	Direct combustion	Yes
	Co-combustion	No
Biogas	Biogas *	Yes
Waste	Biogas from MSW ** landfills	Yes
	Incineration and co-incineration	Yes
	Gasification	No
Energy from the sea ***	Currents	No
	Tidal energy	Yes
Wind power	Terrestrial (horizontal or vertical axis)	Yes
	Maritime	No
Geothermal	Power generation	No
	Air conditioning (closed loop or open loop)	Yes
Hydroelectric	Mini-hydraulic	Yes
Photovoltaic solar energy	Photovoltaic (terraces or facades)	Yes
Solar thermal	Solar thermal	Yes
Thermoelectric solar	Parabolic cylinder	No
	Central receiver	No
	Linear Fresnel collectors	No
	Parabolic Stirling dishes	No

\* Biogas is generated from sewage treatment plants via anaerobic degradation or biodigesters. \*\* Municipal solid waste. \*\*\* IDAE includes wave energy, but the state of development of the technology is “incipient”, so this classification presents the tidal power, also included in [50], which would be available in cities with a coastal border.

Figure 3 proposes a self-sufficient energy model, which maintains the principles of circular UM. The model indicates that the development of renewable energy will decrease the requirement of external energy. This proposal is conditioned on the development, design and management of intelligent networks that enable internal production-consumption interaction and make feasible the optimization and integration of different technologies of distributed generation. This approach will require adapting the network capacity to move surpluses and deficits in accordance with demands and intermittent production of renewable energy. However, the intermittence of renewable sources requires coexistence with generally controllable external energy technologies. In this regard, the promotion of RE in the city does not seek to eliminate the export of energy, but rather to decrease these requirements, whereas the energy storage capacities are limited.

Applicable technologies depend on the existing resources as well as on the user requirements. It is not clear what the best option is from the technological, social, environmental or economic point of view. The choice also depends on the available resources, on intended benefits or the decrease of externalities [51,52]. Eicker et al. [53], for example, consider that photovoltaic solar energy has a greater possibility to supply urban areas, while biomass, wind or hydroelectric power outside the city can supplement the demand. Kanters et al [54] note that solar energy itself cannot supply the demand if it is not accompanied by energy conservation measures and the integration of other technologies, such as wind, geothermal or biomass, with mismatching caused by the intermittence of production-demands.

The study by Moscovici et al. [55] appreciates the use of renewable energies based on a comparison of the ecological footprint (area required for the deployment of equipment and for their manufacture), and establishes that geothermal and hydropower energy are a more appropriate response to wind, solar and biomass. Barragán et al. [56] state that photovoltaic, hydroelectric and biogas technologies from landfills are the most suitable technologies for the production of electric power in a city located in the Latin American Andes.

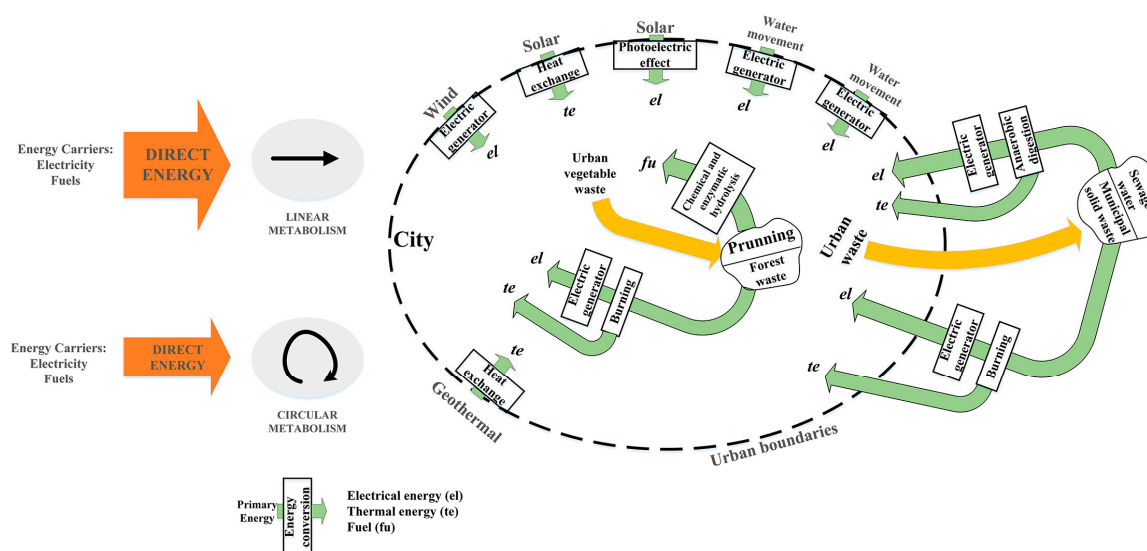


Figure 3. Conceptual model of renewable energy use in a city.

To date, there is no single method for valuing the energy potential within a city. The definitions of energy potential vary and depend on the objectives of the studies. Fath [57] defines the theoretical, technical and economic potential, while Yeo [58] also defines the market potential: (i) the theoretical power is determined by the resource, (ii) the technical potential is characterized by the technology performance, topography or the surface of the ground, (iii) the economic potential is restricted by the technology prices or life span, and (iv) the market potential is related to the regulatory conditions and policies of the locality or to competition with other existing energy sources.

A bibliography that presented proposals to promote the use of the RE in the cities was analyzed. The studies generally analyzed a technology, but also state that there is interest in using several sources in a hybrid configuration. In other cases, investigations are part of more ambitious projects where the incorporation of renewable energy sources is one of the tools to promote urban sustainability. These cases, however, are isolated because, although an increase in the use of RE is pursued, there is still a lack of monitoring tools to establish strategies for the promotion of RE in urban environments [53].

Table 3 presents a set of studies that discuss the potential of using RE to meet a particular energy demand (thermal, electrical, or transport).



**Table 3.** Technical energy potential for different cities.

System	City	Potential *	Demand	Use	Reference	Objective of the Study
Bioethanol	Tartu (Estonia)	93%	1.29 million liters of diesel 0.14 tons of natural gas	Fuel for transport	[59]	Shows that the urban vegetable waste from green areas and gardens can be used to produce biofuels.
	Urban areas of (China)	12.6%	42,334 million liters of petrol		[60]	Determines the energy potential of the waste of gardens for production of ethanol.
Biomass	Leicester (England)	3.3%	—	Thermal	[61]	Investigates the potential for using biomass harvested in the city for thermal purposes.
	Mar del Plata (Argentina)	4.36%	1265 GWh/year	Electric	[62]	Determines the energy potential of forest and agricultural waste.
		3.32%	2912 GWh/year	Thermal		
	Beijing (China)	80%	9501 GWh/year	Electric	[60]	Determines the energy potential of the waste of urban gardens.
	Jiangsu (China)	51%	14,617 GWh/year			
	Qinghai (China)	10%	915 GWh/year			
Biogas	Stockholm (Switzerland)	12%	8300 kWh/per capita/year	Thermal	[20]	Explores the integration of renewable infrastructure to reduce the metabolic fluxes of a district.
	Oakland (United States)	120%	55 GWh/year	Electric	[63]	Examines the use of the technology of anaerobic digestion in the wastewater treatment plants in the United States.
	Mexicali (Mexico)	6%	The percentage is compared with the requirement of lighting	Electric	[64]	Determines the waste from landfills.
	Tijuana (Mexico)	40%				
	Cities in Brazil	100%	107 buses	Fuel for buses	[65]	Determines the number of urban transport vehicles that can be fueled with landfill gas in Brazil.
	São Paulo (Brazil)	7.30%	8723.6 GWh/year	Landfill biogas	[66]	Performs an analysis of the technical potential for the production of electricity using urban solid waste.
	Rio de Janeiro (Brazil)	6.73%	5481 GWh/year			
	Tartu (Estonia)	54.5%	1.29 million liters of diesel 0.14 tons of natural gas	Fuel for transport	[59]	The biogas potential of greening waste was calculated.

Table 3. Cont.

System	City	Potential *	Demand	Use	Reference	Objective of the Study
Incineration	Rio de Janeiro (Brazil)	25.03%	8723.6 GWh/year	Solid urban waste incineration	[66]	Performs an analysis of the technical potential for the production of electricity using urban solid waste.
		12.44%	5481 GWh/year	Incineration of waste-derived fuel		
	Stockholm (Switzerland)	12%	8300 kWh/per capita/year	Incineration	[20]	Explores the integration of renewable infrastructure to reduce the metabolic fluxes of a district.
	Changchun City (China)	29.29%	837.15 GWh/year	Incineration	[67]	This study explores the energy potentials of urban solid wastes.
Wind Power	Wageningen (The Netherlands)	43%	450 MWh/ha year	Electric	[9]	Investigates the potential of a city to provide its own energy resources.
Geothermal energy	Westminster (England)	100%	≈49,000 buildings ≈63,000 buildings	Thermal	[68]	Presents a model for examining the feasibility of installing geothermal energy in the city.
	Ludwigsburg (Germany)	68.69%	873.5 GWh	Thermal	[69]	Develops a model to determine the potential of geothermal energy.
	Cities in Finland	25%	1.3 million m <sup>2</sup> of standard housing units	Thermal	[70]	Investigates geothermal potential to provide heating to buildings.
		45%	1.7 million m <sup>2</sup> of housing of low power consumption			
Hydropower	Beppu (Japan)	100%	29,000 dwellings with consumption of 300 kWh/month	Electric	[71]	Investigates the potential for hydroelectric generation using plants placed in rivers crossing a city.
Photovoltaic	Ostfildern (Germany)	45%	10,700 MWh/year	Electric	[53]	Analyses the performance of renewable energies in urban environments.
	Ludwigsword (Germany)	18%	430,000 MWh/year			
	Munich (Germany)	100%	20 KWh/m <sup>2</sup>		[72]	Assesses the photovoltaic energy potential depending on the design of the building.
	Wageningen (The Netherlands)	50% 66%	45 KWh/m <sup>2</sup> year		[9]	Investigates the potential of a city to obtain its own energy resources.
	Kerkrade (The Netherlands)	18%	481,001 MWh/year		[35]	Proposes a method to identify the energy that can be leveraged within the city.
	Karlsruhe (Germany)	9.5% **	410 GWh/year		[57]	Uses a method that calculates the economic potential of photovoltaic roofs and facades.
	Zernez (Switzerland)	64%	7.4 GWh/year		[73]	Develops a framework for the optimal integration of photovoltaic energy in a villa.
	Cities of (Nepal)	100%	1228 GWh		[74]	Evaluates the feasibility of producing electricity with photovoltaic panels to supply the demand not covered.
	Dhaka (Bangladesh)	15%	773.41 GWh/year		[75]	Discusses the available area of roofs and the energy system is modelled to determine the potential of solar energy.
	Mexico (urban residential areas)	45.6%	29,088 GWh/year	Water heating	[76]	Assesses the potential for solar water heating.

Table 3. Cont.

System	City	Potential *	Demand	Use	Reference	Objective of the Study
Solar Thermal	Spain (8005 municipalities)	68.4%	28,249 GWh/year	Water heating	[77]	Determines the surface of roofs available for the placement of thermal solar panels.
	Concepción-Chile (recent 3233 housing)	75%	19,788.7 MW		[78]	Determines the slope with best qualification by housing according to orientation and inclination, compares feasible joint production universe of study to typical demands.

\* Potential with respect to the demand; \*\* economic potential.

#### 4.1.1. Biofuels

Bioethanol production as a substitute for fossil fuels in transport and energy production has social, economic and environmental benefits. Bioethanol can be produced by breaking the biomass down into sugars or by gasification. The first option is of great interest for so-called second-generation fuels. However, a short-term limitation of this option is that biorefineries for the processing of lignocellulose raw material are in the research and development stage. Moreover, doubt arises due to the land use changes that would be required for the planting of energy crops. An alternative is to use the plant biomass obtained from urban pruning [79] to ensure the benefits from the waste, which does not require more arable areas. Seasonal variation, transport and supply of raw materials, as well as the location of biorefineries, are factors that need to be defined for the operation of this option. However, the availability of the raw material should not conflict with the recreational uses of the spaces from which the vegetable waste is obtained [80]. Bioethanol production using waste from urban gardens can reach up to 12.6% of the annual demand for gasoline in China (42,334 million liters) [60]. In Tartu (Estonia), it was estimated that 93% of public transport fuel could be replaced with bioethanol produced by forestry waste from regularly maintained park and public greenery, private gardens and courtyard areas [59]. Generally, the plant residues are combined with common urban wastes to be sent to landfills. Therefore, management policies are required for their proper selection, processing and transport before sending them to biorefineries [60].

#### 4.1.2. Biomass

Like hydrocarbons, biomass has its origin in living organisms [81]. The residual biomass obtained from the operation of urban pruning can be used in industrial applications for the production of steam, power generation or transport [65,81]. Biomass for energy may cause severe environmental damage or impact on the provision of food, while biomass coming from urban area waste is an alternative, because urban waste would have less ecological value or agricultural importance [52]. The maintenance of gardens provides an added value to this activity, because debris can be used for energy purposes [60]. Unlike the energy crops or forest biomass, garden waste would be ready to be transported, and its alternate use would reduce the costs of provision.

Municipal waste is a resource being misused and even represents a management problem. Inorganic waste (paper or plastic) can be recycled in industries. Organic waste, through chemical processes, can be converted into nutrients or can be used to produce electrical energy or heat [82]. The treatment of solid waste in landfills brings as a benefit the reduction of greenhouse gas emissions, leachate management, and retention of dangerous pollutants [83].

Saha et al. [84] estimated that obtaining energy crops from marginal urban land can yield 230 GWh/year, equivalent to 0.6% of the primary energy that is required by the state of Massachusetts in the United States. In a study by Kook et al. [81], the potential energy resources for five South Korean cities (Seoul, Daegu, Daejeon, Gwangju, and Busan) were estimated as a preliminary step to determine the most appropriate choice of process for converting biomass into energy. In the study, the resources are classified depending on the sectors of origin: (i) agricultural bioproducts, (ii) forest products, (iii) livestock waste, and (iv) urban solid waste. The analysis concludes that even when the biomass from forest products has the highest energy potential, urban wastes can be the most important resource for use because they have a high energy density by area.

The use of biomass from pruning and garden waste for energy purposes has not been fully investigated [60]. McHugh [61] revealed the potential of short cycle vegetation to be used as fuel for district heating in Leicester City (England). The analysis concludes that with the biomass available, it is possible that 3.3% (4200 housing units) of the thermal demand can be supplied. In China, the potential supply of electrical energy from waste from gardens varies between 10% and 100%, depending on the city [60].

For Mar del Plata City in Argentina, the biomass potential for electrical and heating purposes was determined; the analysis included both the resources from agriculture and those from urban forest

residues. The total production would supply 23% and 10% of the electrical and thermal demand. When considering only the potential of urban biomass, the contribution is 4% and 3%, respectively [62].

#### 4.1.3. Biogas

There are several sources for obtaining biogas in a city: industrial waste, urban pruning waste, urban solid waste, the organic fraction of municipal solid waste, and municipal wastewater or wastewater from industries. The production of biogas by anaerobic digestion for purposes of electrical or thermal generation or as transport fuel can be obtained from waste from vegetable pruning, gardens, food, from landfills or the black waters of cities.

The study by Van Meerbeek et al. [85] determines the biomass potential of conservation area and road edge pruning in the region of Flanders (Belgium). In this case, pruning produces 721 GWh to provide power for 205,000 homes. However, it is not considered profitable from an economic point of view.

Arodudu et al. [52] calculates the energy potential of biomass from rooftops, parks, waste from gardens or food and seasonal leaf drop in the region of Overijssel (The Netherlands). The exploitation is based on anaerobic digestion for biogas production. The development represents between 0.6% and 7.7% of the regional objectives for 2030. However, in this case, the production is not environmentally sustainable, since the relationship of input/output of energy is not efficient [52]. Even so, this author considers that this condition could be reversed in developing countries that require less demand for energy.

Biogas from municipal solid waste is related to its composition and quantity [64,65]. In developing countries, where waste reduction is not consolidated (by re-using, recycling or prevention), an increase in waste disposal is expected, at least in the midterm [86]. In Africa, high rates of collection could supply 9% or 4% of the average continental per capita consumption of electricity, with incineration technologies or biogas, respectively [86]. In the metropolitan cities of India, the disposal of waste in landfills would allow the recovery of 60–90% of biogas suitable for the production of energy or to obtain fuel [83]. In Mexicali and Tijuana (Mexico), the generation of energy from landfill gas could compensate for 6–40% of the demand for lighting, respectively [64]. In São Paulo and Rio de Janeiro (Brazil), the calculation by Souza et al. [66] shows that the production of biogas could compensate for approximately 7% of the electrical energy.

Another option for the biogas in Brazil is fuel provision for approximately nine-times the fleet of existing urban buses (10,700 units) [65]. However, using this fuel would require a modification of the combustion system of the vehicles. Positive effects, not valued completely, would be the reduction of emissions and pollutants that affect the health of the urban area inhabitants.

The recovery of biogas from wastewater can be used for the generation of electric, thermal, or cogeneration fuel for vehicles or for injecting into natural gas networks. In the United States, it is estimated that less than 10% of the sewage treatment plants take advantage of biogas for thermal or electrical purposes. The energy is used mainly to reduce the external consumption, although, depending on the plant production, the energy can be exported [63]. Pandis Iveroth et al. [20], for example, estimated that 12% of the district heating for Stockholm can be provided with this source.

#### 4.1.4. Incineration

The controlled disposal of wastes, in addition to allowing the separation and recycling of materials, serves to produce electrical or thermal energy. Urban solid waste for energy purposes can be transformed into energy by the extraction of biogas or incineration. In the case of incineration, burners are used that allow the operation of steam turbines [87]. If humidity conditions or organic matter present in the waste do not allow the production of biogas, other techniques of energy utilization can be applied. The energy contained is retrieved by thermochemical processes (pyrolysis or combustion) or through biochemical processes (anaerobic digestion). The use of incineration technologies currently presents technical or economic difficulties, while gasification and pyrolysis are not available on a

commercial scale [86]. Using incineration techniques to produce fuel recovered from waste or municipal solid waste can increase the production of energy two and four times, respectively, with respect to the biochemical processes [66].

#### 4.1.5. Wind Power

This renewable technology is regarded as clean, affordable and secure. Mainly, its promotion has been for equipment on a large scale, while its implementation within the city is modest. Inadequate valuation of the wind is a factor that must be considered to avoid incorrect location of turbines in urban environments [88]. Shu et al. [89] make a statistical evaluation of the features and energy potential from wind. The study found that in urban areas, there is a possibility for turbine operations to produce 7.97%, with speeds of 2.55 m/s and a power density of 24.20 W/m<sup>2</sup>, compared with 90.19%, 9.04 m/s, and 915.93 W/m<sup>2</sup>, respectively, when compared with hills or coasts. This difference is because, in urbanized areas, buildings reduce the wind speed. In another study developed in Leeds (England), it was suggested that wind conditions of 4 m/s could result in deployment of more than 9000 turbines on tall buildings [88].

Even when the placement of micro wind turbines may be appropriate in areas with low urbanization [90], with buildings of similar height, the decrease in wind speed can be an impediment to its optimum performance [88], which adds to the constant change of the urban profile for new buildings. It will require planning, design and a particular analysis of each case, including aspects related to turbulence, noise, size, space, visual impact, security [91], geometry, architecture of the buildings and obstacles in the city [88]. Both the visual pollution and problems due to vibration and noise are barriers to optimal architectural integration.

Applications in cities have been reported in specific projects. The various morphologies of the city (buildings, streets, trees or other obstacles) and the maturity of the technology have prevented the performance of studies that reflect the potential within a city. Of the two types of arrangements (vertical and horizontal), it is expected that, in the forthcoming thirty years, technologies for the vertical axis will be common in urban environments [91]. The placement of wind turbines is not only found on masts placed on rooftops, but may be integrated into buildings, placed between two buildings, integrated into a building's skyline or placed to take advantage of the airflow in a double-skin façade [92]. Wind power installations have a number of advantages, such as user empowerment, greater overall efficiency, avoidance of transport losses due to proximity to the load, and more that do not require the installation of an additional electrical infrastructure [50]. Despite the above advantages, aspects such as safety, shadows, noise, vibration or visual impact [91,93] are conditions for the use of this technology, which is why more research is required for use in urban environments.

#### 4.1.6. Geothermal Energy

Geothermal energy production exploits the temperature difference between the air and the earth's sub-surface to extract heat. Extraction requires electricity to operate a heat pump to draw the geothermal energy. The analysis on profitability should therefore consider the valuation of the coefficient of performance (COP). Geothermal energy has not been extensively studied, despite being a resource with unlimited availability. Geothermal energy does not depend on external factors, as aeolic (wind) and solar (radiation) energy do [69]. The geothermal capacity is profitable in places with important thermal oscillations (winter-summer, day-night), where constant temperature under the ground can be more profitable, even without a heat pump.

The geothermal heat pump (GSHP, ground source heat pump) is a technology that allows the transfer of stored heat from/to the floor to heat/cool buildings. For spatial reasons, systems used are those emplaced vertically, at depths between 50 m and 100 m, and where the temperature is constant. They are classified as two types of systems [68]: (i) closed loop, in which an antifreeze fluid passes through underground pipes, and (ii) open loop, needing an aquifer from which water is extracted directly with a heat pump to complete the heat transfer.



Zhang et al. [68] assessed the implementation of closed-loop systems in Westminster, London, where there are nearly 96,000 buildings of various types. Two simulated scenarios are defined by the area required for placement of vertical wells (under or around the buildings). Between 51% and 66.6% of buildings can be supplied with the disposal wells underneath or around them. In Ludwigsburg, Germany, the model made by Schiel et al. was tested [69] to determine the potential for a geothermal energy plot to provide heating and hot water. A theoretical 40% of the plots could supply 100% of the demand.

In Finland, between 25% (houses) and 40% (detached houses with a low energy consumption) of residential buildings built annually can be equipped with heat using geothermal open-loop energy [70]. This technology use is limited by the geological and geothermal conditions of the subsoil of the cities. In the cities of Turku, Lohja, and Lahti, Arola et al. [94] studied the effect of heat islands in urban centers on temperature variation in groundwater. The temperature is increased 3–4 °C, indicating that in urban centers, heat islands can take advantage of a maximum heating power of 50–60% compared with rural areas. On the contrary, the decrease in power of maximum cooling is approximately 40–50%.

#### 4.1.7. Photovoltaic Energy

Analysis using 3D for assessing solar potential in cities is becoming common since it allows the consideration of the effects of shade (trees, buildings), facade and roof surfaces [95,96], and urban density and orientation [54]. However, computational efforts and prior rendering of the urban environment to be evaluated is required [96]. PV technology can potentially integrate buildings and urban equipment; the tendency is to adapt coating products or accessories and integrate them into urban architecture [97].

The interest in this technology in urban applications contrasts with the various designs of buildings that prevent achieving optimal sun conditions. Locational conditions are relevant; buildings close to the equatorial line have a preponderant collection on the roof, while it is limited in façades. On the contrary, in Mediterranean areas up to high latitudes, the facades gain importance for solar energy production. Sarraide et al. [98] evaluated the relationship between building shapes and the solar potential of roofs and facades. This study shows that facades have limitations for solar energy use (four times less compared with the base-case scenario that uses panels on the roof). This result, however, depends on latitude and proportion of direct and diffused irradiation, in addition to architectural conditions, such as the distance between facades. Other issues to consider are the built area (floor space index (FSI), which is the ratio of a building's total floor area to the area in which it is constructed) and the rotation of the building. Kanters et al. [54] note that only with a low FSI (less than 1), can a coverage of 100% of electricity be achieved, under certain conditions of demand and irradiation. Zalamea [99] shows that roof area availability and architectural features of dwellings are determinants, so that in the same locality, it is feasible to take full advantage of irradiation, reaching a catchment that exceeds 100% of the demand if there is a surface without obstacles, compared to 10% if the roof is irregular and divided. However, in the same context, because of system restrictions of the existing grid and seasonal fluctuations, only between 15% and 27% could be covered [100].

Chaianong et al. [101] describe the current situation as an opportunity to include photovoltaic systems (on rooftops) in Thai cities. It is argued whether the participation of these systems brings environmental benefits, diversification or energy autonomy. It is emphasized that it is a proper response to a high degree of urbanization and demand growth. In the case of Nepal, the use of photovoltaic technology is promoted to supply the demand not covered by electricity from the network [74]. This author finds that using 10% of the roof areas in the cities would provide the energy the country needs to cover the unmet demand.

Research in Karlsruhe City (Germany) considers the photovoltaic technology on rooftops, integrated or not with the building (modules assume the role of protective materials from rain or solar control) [57]. In the town of Zernes (Switzerland), the model developed by Mavromatidis [73] was applied. This model includes the calculation of solar potential, daily power demand and cost

restrictions (investment in panels, storage system, energy received, produced and maintenance). Peak power calculated at 3150 kWp is obtained from the maximum surface available for the installation of panels (25,200 m<sup>2</sup>). As per the restriction of costs, it can be between 25% and 64% of the demand.

Radomes et al. [102], for Medellin, Colombia, makes an analysis that evaluates the amount of installed power with photovoltaic panels that may be installed by 2035 as a horizon of analysis. To aggressively encourage the placement of panels, the implementation of incentives is required (subsidies or regulated rates), requiring that for an increase of 0.26 MW (70 users) to 5.85 MW (1657 users), 4.5 million dollars are needed for the first year of implementation.

Rosenbloom et al. [103] reviewed the situation in Canada and established that photovoltaic technology can produce a significant amount of energy. However, in addition to the technical constraints (resource variability, area availability, efficiency), issues related to the economy (equipment and installation costs and energy prices), society (acceptance, “sun tax”), environment (plate fabrication lifespan) or other industries (existence of low-carbon energy sources) must be considered. On a global scale, the International Energy Agency predicts that by the year 2050, integrated photovoltaic roofs could supplement 32% of the urban demand and 17% of the global demand for electricity [104]. Social acceptance and architectural aspects are considered, since there has been considerable development of PV products for architectural integration as building integrated photovoltaics (BIPV) in the last decade [105].

#### 4.1.8. Solar Thermal

This technology is used in different countries, with different penetration levels, for solar water heating (SWH) for domestic use, industrial applications or for ambient conditioning (heating or cooling). Because of the variability of the resource, the use of this technologies is usually accompanied by a back-up system (electricity or fossil fuels), which guarantees thermal comfort conditions. The technology is available for applications in individual homes, buildings or urban districts.

In Mexico, in the urban residential sector, 45.6% of liquefied petroleum gas used for water heating can be replaced by solar heaters. Although there is a national market for solar heaters, and it could be an economical alternative when compared with the use of liquefied petroleum gas or natural gas, the lack of incentives prevents this option from expanding [76]. On the contrary, in the cities of Haining, Huzhou and Ningbo (China), where solar water heaters are fabricated, more than 90% of inhabitants use this equipment. The success of the dissemination of these systems is due not only to the lack of fossil resources but also to an industrial structure, economic incentives and municipal policies. In addition to the solar thermal technology, a positive image of the use of this technology was developed, which has allowed broad public acceptance [106].

Izquierdo et al. [77] conclude that 68.4% of the hot water requirements can be supplied with the use of SWH in 8005 Spanish municipalities. Accomplishing this level of usage requires less than 20% of the rooftop surfaces, leaving the rest available for the installation of photovoltaic panels.

The influence of shadowing is less with this technology when compared with photovoltaics. Marique et al. [107] show that urban density affects the production of thermal energy because of the area available for the placement of thermal panels. In areas with lower housing density by surface, a lower production of energy is obtained. In the case of a FSI with values below 1.5, the thermal demand can be fully provisioned [54].

#### 4.1.9. Other Technologies

The energy of the sea can be exploited using various technologies, including tidal currents, ocean thermal energy conversion, waves or osmotic power [50]. In tidal power, a reservoir is required, which can be a bay and an estuary. The requirement of a reservoir can be a limiting factor, since the space is not always available. If restrictions due to environmental impacts are considered, as well as the high capital and the construction times, restrictions are increased for installation in urban areas. In the city

of San Luis (Brazil), an analysis was carried out to maximize the energy of a plant with 11 turbines, which would produce 41 GWh per year [108].

Similar to tidal power, hydropower is an option for the provision of electric energy. Under the UM approach, its implementation would be subject to the condition that the resource be within the city limits. Moscovici et al. [55] suggest that for Philadelphia (USA), an alternative to enable sustainability and self-sufficiency is the construction of small hydroelectric stations within the city limits. Fujii et al. [71] find that the demand of up to 29,000 dwellings could be supplied if hydroelectric plants of less than 1000 kW are used, installed in the rivers that cross the city of Beppu (Japan).

The investigation by Zhou et al. [109], which was much more ambitious, proposed to alleviate air pollution in Chinese cities with the use of solar towers. The hot air caused by the islands of heat in the city is led through chimneys 1–1.5 km in height, which would carry the pollutants to the upper atmospheric layers so that they can disperse. This technology can be particularly useful in cities where thermal inversion occurs, preventing the dispersion of polluted air. The study also analyses the placement of a 12.5 MW generator in the lower part of the tower, whose turbines are moved by air currents producing up to 39.9 GWh of electricity.

The use of oil residues is analyzed by Song et al. (2016), who state that for Changchun City (China), biodiesel can be a successful solution that, in certain scenarios, would exceed 100% self-sufficiency.

#### 4.1.10. Integration of Technologies

Several research technologies complement each other. Combining technologies seeks to ensure that the provision of energy replaces different uses of non-renewable sources, and aims to maximize supply, given that the primary resource may not always be available. The integration and association of intermittent and controllable production is important to stabilize the network.

Eicker et al. [72] evaluate how a neighborhood design in Munich influences the provision of electric energy or heating that can take advantage of photovoltaic solar panels or a geothermal plant, respectively. While the thermal demand can be reduced by 10% if buildings are compact, shadows may cause an increase of up to 13% of the energy demand. With a specific distribution, the electrical demand can be overcome, and if shadows are considered, it decreases by 25–32%.

Sarralde et al. [110] assess RE potential (solar, geothermal, wind or biomass). The proposal uses nine indices related to soil use, area available and demand. This study aims to help understand how renewable energy can be integrated into urban environments.

The model proposed by Yeo et al. [58] uses geographic information systems and artificial neural networks to determine the location of energy supplies and renewable energy plants. The model is applied in the urban districts of Gwang-myung/Si-heung, Gyeonggi-do, South Korea. The study includes photovoltaic technologies and wind turbines (vertical and horizontal axis) and highlights the implementation limitations of wind turbines either by the availability of winds or by the limitations of power.

As a step to developing energy self-sufficiency in Dakha (Bangladesh), the study by Matin et al. [111] explores the incorporation of photovoltaic energy and biogas plants in a set of commercial buildings. In addition to the technical design, very general costs of the equipment as well as the price of energy are set. For urban and semi-urban areas, Marique et al. [107] extend the concept of buildings with zero energy to sectors comprising several buildings. This study analyses the use of wind, solar thermal and photovoltaic technologies, and proposes the use of the latter at the community level rather than at the individual level. The impact of efficient and sustainable management is affected by the thermal insulation of buildings and consumer behavior.

Orehounig et al. [22], through an optimization model that includes both economic and emissions restrictions, proposes the integration of photovoltaic energy, mini-hydro and biomass, using the concept of an energy hub. A decrease of 38% of CO<sub>2</sub> emissions is achieved by reducing the consumption of fossil fuels and electricity from the network. The same author demonstrates that when applying this

concept in the village of Zerne in Switzerland, free of economic restrictions, emission reductions reached 86%, and there was a renewable energy substitution of 83% [112].

#### 4.1.11. City Projects

The “Energy Efficient Cities Initiative” (EECI) project in England is a multidisciplinary research program seeking to reduce the demand for energy and environmental impacts in cities. Among the objectives of this project is to ensure that renewable energies are considered for urban planning and are integrated into the buildings or urban spaces [113,114].

The MUSIC (Mitigation in Urban Areas: Solutions for Innovative Cities) project has as its objective the reduction of energy consumption and the decarbonization of cities. This project brings together the participation of research groups from Scotland (UK), Ghent (Belgium), Montreuil (France), Ludwigsburg (Germany), and Rotterdam (The Netherlands). This project developed a tool that enables the assessment of renewable energy potential so that planners can choose the location and type of energy that can be applied [115].

In recent years, there have been several instances, at varying scales, of urban insertion of renewable energy as a result of the adoption of public policies, local incentives and specific strategies. The success achieved in all cases is relative, and depends on local conditions and, to a large extent, on the environmental conditions and natural resources available. A detailed compendium of these experiences has been published by the International Energy Agency [13] and The International Renewable Energy Agency [116].

#### 4.1.12. Maturity of Technology

The expansion in a renewable technology will depend on its maturity because it is the commercial level (C) that determines whether it is ready to be used. While technologies are at the level of research and development (R & D), they are being tested in the laboratory. Those that are in the demonstrative stage (D) have pilot plants, and there is no defined horizon for their application. Table 4 shows that, with the exception of wind technology and second-generation bioethanol, all other technologies are in the commercial stage. Wind technology has reached the commercial level, which makes it applicable in rural environments. However, wind technology requires more technological progress for its application in urban environments [117].

**Table 4.** State of development of technologies.

Sector	R & D	D	C	References
Biofuels second generation	X	X		[118–120]
Biogas from wastewater			X	[63,121,122]
Biomass			X	[62]
Biogas landfill			X	[66]
Incineration			X	[66]
Hydroelectric			X	[123]
Small wind	X	X		[117]
Photovoltaic			X	[50]
Solar thermal			X	[124–126]
Geothermal			X	[50,69,127]
Tidal			X	[50]

## 5. Discussion

The conditions for sustainability development require that there is no growth without considering the regenerative capacity of materials and energy. Therefore, a city should not exceed its ability to dispose of its waste ahead of its input of materials and energy [19,37]. The city, then, should manage its resources in such a way that (i) the renewable resources that it requires should not exceed its rate of regeneration, (ii) its emissions should not exceed the capacity of ecosystems to assimilate waste,

and (iii) the non-renewable resources required are not exploited in such a way that their depletion rate exceeds the creation rate of renewable alternatives [35].

Huang et al. [29] state that intensive urbanization and industrialization accelerate entropic processes, which will lead to a “bleak future for life”. Moreover, Huang et al. [36] emphasize the need to close the cycle of inputs and outputs, ensuring the future availability of resources. Niza et al. [39] emphasize that sustainable development in urban areas consists of resource management by protecting the environment in the long term. This task has become paramount, as Barles [41] demonstrated that urban areas import far more than their consumption requirements.

UM, as a tool, provides valuable information to be used for structure analysis, organization, and resource uses, as well as environmental impacts related to human activity in the city [10]. UM seeks to understand the processes that are developed in the city [25]. This understanding can then be applied to the practical field through the adoption of public policies to reduce ecological footprint of a city [11]. A comprehensive and holistic approach to understanding the city can help the organizational and administrative bodies to make decisions. In this sense, the quest is to promote solutions that will enable the maintenance of human quality of life without exhausting the planet’s resources, and, at the same time, avoid altering the dynamics that support the civilization [23] as it is known.

Through applying UM principles, valuable information can be obtained to develop an analysis of structure, organization, and resource depletion, as well as environmental impacts related to human activities in a city context [10]. If energy flows in an urban area are known, then finding energy substitutes from renewable sources available in city boundaries is possible. Therefore, a comprehensive and holistic approach to understanding the city is required to consider the energy issue also at the regional or national level. Agudelo-Vera et al. [9] express that resource management is the key factor for sustainable urban planning. Based on the management of resources, a public policy that motivates this knowledge would allow planning cities to limit, reduce or replace the use of external resources [19].

Urban settlements in the 20th century should be salubrious, according to conditions and infrastructures developed from policies based on scientific knowledge, to provide basic services or decrease the disease incidence for the majority of the population. The 21st century paradigm should change since cities will face environmental challenges and scarcity of resources. Urban planning considering energy requirements as milestones should be proposed to encourage communities to import less energy [1,2]. In new urban areas, planners should, from the beginning, be able to establish the city’s conditions, so they should be able to integrate bioclimatic principles or renewable technologies into the buildings.

To contribute to renewable energy development at the regional level, long-term strategies aimed at developing sustainable energy systems based on local resources should be established. Each place possesses different natural resources and energy and material demands [49]. Barragán et al. [56] described 14 factors that should be considered for renewable technology development based on the sources available in a city. These authors suggest that each urban area has particular conditions from which it is possible to choose better alternatives, and that the technology potential for one place does not necessarily correspond to that of another. The results of an international survey suggest that the existence of the resource, operation and maintenance costs, job creation or community empathy would be decisive factors for the implementation of one technology or another.

Several investigations have detected the capacity of urban centers to fully or partially self-supply energy. In Tartu (Estonia) the capacity to obtain bioethanol with urban waste was valued, and it is determined that 93% of the fuel demand for public transport can be replaced [59]. In Mar del Plata (Argentina), 4.36% of electricity can be supplied from urban forest waste [62]. In Tijuana (Mexico), 40% of the artificial lighting can be supplied with biogas from landfills [64]. In Stockholm (Sweden), 12% of the electricity can be obtained from waste incineration [20]. In Westminster (England), the thermal requirements of 63,000 homes could be supplied by geothermal energy [70]. In Beppu (Japan) mini-hydro stations have the potential to power 29,000 homes [71]. In Zerne (Switzerland), 64% of



the demand could be absorbed by using photovoltaic energy [73]. In Concepción (Chile), 3233 homes can cover their energy needs for hot water and electricity from solar thermal and PV [78].

In the studies cited, autogeneration within a city has its limitations and will depend on the remedy available, the type of consumption per capita or the conditions of implementation of the equipment as well as a correlation in seasonality of demand—potential of renewable resource. The maximum power that could be exploited is conditional, depending on technological efficiency, typology of the city or demand-supply patterns. Without the adoption of measures concerning early urban policies, it is not possible to promote urban energy utilization effectively, especially on a large scale. Therefore, political involvement is essential.

Most of studies reviewed found, in most cases, the potential to cover the demand of a single type of energy source. An integral analysis requires studying several possibilities together for substitution of energy carriers, as well as the application of the aforementioned complementary measures. In large urban settlements, the possibility of establishing policies aimed at the adoption of renewables may be more complicated. Therefore, the integration of renewable energies and the timely adoption of policies that promote them may be more feasible in intermediate cities.

In the face of the obvious advantages of renewables and the restrictions to increasing their participation in the energy mix, several countries are looking for options to encourage the use of renewables, mainly in large-scale installations, that in many cases are located far from the sites where the demand is concentrated. The lack of capacity to obtain supplies of autochthonous resources for energy generation has been one of the research lines that has increased in recent years. The alternative is urban energy self-sufficiency as a measure for controlling the import of energy and use of the endogenous resources the city has. Justifications to encourage renewable energy use in the urban environment are as follows:

- The high density of the population concentrated in cities offers opportunities for achieving economies of scale [11], promotion of the development of new jobs, and the growth of the gross domestic product (GDP) [128]. Llera and colleagues [129], mention that the economies of scale at the same time influences jobs requirements between 1.7 and 14 compared with natural gas or coal power plants.
- Increasing GDP and decreasing the intermediate consumption of energy will increase the value added [40].
- It is appropriate to perform an analysis and to suggest actions (of emission reduction or energy savings) at the local level (cities, towns or urban districts) [130].
- Self-provision decreases uncertainties in the energy supply due to externalities [42] and reduces large energy production and transport infrastructures [4,55]. It also allows reductions in the consumption of fossil fuels. In addition, the area requirement for energy production is reduced as transmission networks decrease. Social changes in energy use require changes that influence the implementation of policies that fall under the principles of sustainable development [46,51].
- Rapid urbanization can be used as an opportunity to change the future of cities if they are conceived of as systems in which energy flows can be used in an efficient manner. [131]. Energy supply efficiency is promoted because the losses associated with transport from long distances will decrease [55,103], and there will be a reduction in raw material consumption since it avoids losses by energy transformation [51]. In addition to the use of non-renewable resources (lower consumption of fossil resources), distributed energies are close to the points of consumption (increases energy efficiency), reducing energy dependence and increasing safety and reliability [93,127].

The integration in districts is another advantage that is discussed, in terms of efficiency, since it implies the integration of systems that include several technologies (electrical, heating and cooling networks) and that at the same time serve several buildings [112]. Electricity production technologies are also faced with the fact that the networks are designed for a unidirectional electric flow, since passive consumption points would become energy producers.



Ren et al. [18] argue that the energies distributed in the city allow for the reduction of CO<sub>2</sub> emissions, however they have economic disadvantages because of their high initial investment. Renewable energies are more capital intensive (if compared with the technologies that use fossil resources), so their costs make them less attractive when choosing them as substitutes for conventional generators. Therefore, for the dissemination and proliferation of a technology, an initial stage is required to boost its promotion through subsidies or loans until the industry is well established.

The cost per kW is influenced by the extent of the dissemination of the technology and the technology's maturity, so higher power costs normally correspond to small systems. However, there are technologies, such as photovoltaic or solar thermal, that could be expanded throughout the city in domestic systems, while mini-hydro, tidal, biomass or biogas systems would be limited to one or a few dispersed plants. Since energy in the city is not expected to be produced in large power plants, an economy of scale related to huge production centers is not expected, in fact, this is an advantage of multi MW projects [103]. It is understood in this case that an economy of scale can be achieved with the possibility of expanding the manufacture and assembly of the renewables devices, which in the long run will cause a decrease in the equipment cost [55], encouraging its use and economic convenience.

Although RE can reduce the problems associated with the access to and availability of energy, the new technologies cannot necessarily eliminate the problems. For example, renewable resources are intermittent (solar and wind energy), and this makes them dependent on the presence of the resource, i.e., the resource may not be available at the time that the system needs to supply energy [132] on a Smart Grid configuration with dependence on variable sources. Given the intermittence of some renewable resources, it is necessary to maintain the external energy supply or improve the storage capacity of energy. While it is true that the storage of electrical energy can be a solution, more research is required to make it a viable technical and economic option [112]. Thermal storage, which has a lower cost, is a mature and widely used option [106,133].

Energy sources from natural gas (0.31 km<sup>2</sup>/GWh), coal (4 km<sup>2</sup>/GWh) or nuclear energy (0.5 km<sup>2</sup>/GWh) require less occupation area than the large-scale PV solar farm or wind farm requirements of 45 km<sup>2</sup>/GWh and 72 km<sup>2</sup>/GWh, respectively [134]. Urban integration of some of these technologies, such as geothermal, solar thermal, roof photovoltaic or small wind farms, do not require space outside urban boundaries [135]. Other facilities, such as biogas, biofuel, incineration or hydroelectric plants, may require places nearby the urban area (landfills or water treatment plants). However, these conditions are specific, and as suggested Barragán et al. [56], each city must analyze their specific potentials against energy requirements. When using an already intervened space, it would cause fewer impacts compared to large-scale facilities located in the countryside.

The possibility of creating self-sustaining urban areas with their own resources seems to be unviable currently. It is estimated that in the best case, mega cities could be supplied with approximately 1% of their energy requirement from renewables distributed within the urban limits [2]. As Georgescu-Roegen [136] suggest, it is necessary to continue to develop the technologies with the most potential in order to promote a change in the way energy is managed within the city.

Energy is not the only aspect of urban sustainability; a more political vision of urban management corresponds to the "Smart City" concept. This innovative proposal is aimed at improving the quality of life of city inhabitants through networking management and technologies (ICTs) that improve the efficiency of mobility, provide greater security and encourage the rational consumption of resources or compact and accessible urban forms [4]. Within this conception of energy management corresponds to the Smart Grid concept, which are strategies related to the adoption of renewables into buildings and urban deployments, using efficient equipment, and networking ready for energy flows in different directions [5].

In the future, it is expected that the development of intelligent power grids will facilitate coupling technologies and will consider energy source instability. The joint inclusion of different renewable technologies, with an emphasis on the non-polluting ones, is essential; the intermittence of solar, wind

and even mini-hydro may be corrected between them, then this imbalance can be complemented with biomass or biogas, that can serve as controlled production.

Technology would help to cover the energy demand; however, it requires a behavior change oriented towards avoiding unnecessary material and energy consumption. Georgescu-Roegen [15] supports a change of decisions and behavior (a Minimum Bioeconomic Program) in which the use of natural resources or energy waste are considered. At the same time, it is conditioned on structural changes of humanity, such as a gradual reduction of the population, discarding equipment or futile customs of fashion, and the redesign of consumer goods, among others. The behavior of the inhabitants with respect to the consumption of materials and inputs or the use of energy services or transport has a direct relationship with a linear model to a circular model change.

## 6. Conclusions

Several investigations related to urban metabolism suggest the use of renewable energies to reduce the importation of energy. However, to promote circular metabolism, energy production must correspond to available resources (wind, sun, heat and water) within the city or that come from the city (waste or wastewater). This review identifies technologies that facilitate a change in the urban energy model. The suggested model avoids relying on endogenous resources while also exploiting urban waste. Eleven energy systems that have different abilities to replace these external flows and promote circular metabolism have been identified.

The application of the technologies will depend on availability, so there must be an inventory of available resources and energy demands. Most studies are applied to a single technology, but the photovoltaic plant is the one that has aroused the most interest. With different potentials according to the urban environment, location and energy requirements, electricity has an increasing ability to absorb all types of urban demands, including thermal and transport. Technologies, such as solar thermal or geothermal, can be complementary, either for air conditioning or water heating, and can be applied individually. Other technologies, such as biomass, biogas, hydroelectric or marine currents, require increased infrastructure to be applied to districts or blocks of departments, although they are an alternative as a complement to intermittence of production-demand. Wind technology has difficulty in adapting to the urban environment, but there are proposals that promote its mass distribution.

The possibility of reducing energy inputs to cities is indisputable. The intention is that urban planning should include measures to ensure that these technologies are gradually accepted and fiscally integrated, according to the autochthonous resources and conditions. It is proposed that energy planning should expand to the town level and not remain only at a country or regional level. Comprehensive urban energy planning requires identification of the existing renewable potential and potential uses as per the available technologies. At the local level, planners should define the uses of energy, proposing milestones to allow the communities to be autonomous.

Undoubtedly, other alternatives promote sustainable urban management and should not be overlooked, including energy efficiency requirements, passive strategies, technologically-efficient substitutions or the development of external renewables. A city is unlikely to obtain total energy self-sufficiency by using only endogenous resources, at least in the short term. Any proposal intending to change the paradigm of how the city is conceived will mean a change of attitude at different scales (authorities, planners or citizens) in the way the city is planned.

Since society inevitably leads to changes in the environment, it is necessary to anticipate these changes. In that sense, UM is a tool that allows monitoring and defining strategies to ensure an adequate quality of human life while undergoing these changes, even though for any city, there would be numerous possibilities and technologies that should be evaluated and that may complement each other. The use of renewable technologies at an urban level is being investigated, but the particular conditions of a city, the location or energy requirements of the city, limit the extent of the use of renewable technologies.

Understanding UM, energy resources and renewable technologies will make it possible to propose application policies for one or several technologies. The development of energy resources available to a city will reduce its dependence on non-renewable resources and pollutants. It is essential that a society be more committed to ameliorating environmental problems. Energy self-sufficiency is a way to achieve sustainable development. These and other actions must undoubtedly be considered, because the success of current human development can leave a catastrophic legacy that future generations will be forced to face if there are no changes in the consumption of materials, water and energy.

**Acknowledgments:** The authors thank the Fundación Carolina and Universidad Politécnica Salesiana. This research has been supported by Dirección de Investigación de la Universidad de Cuenca, DIUC. It is part of the “Abastecimiento energético renovable desde recursos endógenos, en ciudades de países en vías de desarrollo en el marco del metabolismo urbano. Caso de Estudio Cuenca, Ecuador” research project.

**Author Contributions:** Antonio Barragán-Escandón structured the article and carried out the bibliographic review. Julio Terrados-Cepeda reviewed and suggested changes in content. Esteban F. Zalamea-León contributed to the analysis of the concepts of urban metabolism.

**Conflicts of Interest:** The authors declare no conflict of interest.

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