Investigating the city-level correlation between energy consumption and economic growth

A review and way forward

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Abstract

This paper reviews the nexus between energy consumption and economic growth, and identifies causal relationships. In contrast to most of the literature in the field, this review focuses primarily on the city-level relationship between energy and economy. A country-level understanding of the relationship was reviewed in order to find context for the city-level investigation. Despite the fact that there is a widely recognised positive correlation of energy consumption with economic growth, there is no established consensus on the correlation coefficient or magnitude of relationship between energy consumption and economic growth, and there is limited understanding of the causal mechanisms responsible. This review identifies energy intensity, energy cost share and energy return on investment as useful metrics for understanding the relationship between energy consumption and economic growth. Furthermore, it provides an increased understanding of economic development and its influence on the growth of cities in the context of sustainable development. While increasing energy consumption will further economic development and city growth, there is an increasing need to decouple resource consumption and environmental impacts from increased energy consumption. This paper identifies and discusses various key focus areas (energy efficiency, decoupling, and the unrecorded economy) and their impacts on the energy-economy nexus and discusses their relevance for the sustainable development of cities.

Keywords: energy transitions, cities, economy, energy planning, policy

1. Introduction

The relationship between energy consumption and economic growth and its importance for energy policy has been highlighted by Karanfil (2009): ”*The implementation of economically efficient energy policies and the prediction of the impacts of various energy and economic policies require an understanding of which of these variables causes the other.”*

The causality between energy consumption and economic growth is then well studied in the energy-economics literature (Karanfil, 2009; Ozturk, 2009). Different studies have focussed on different countries and time periods (Aucott and Hall 2014; Arshad et al. 2016). Most of the studies on the energy-economy nexus are aimed at informing national energy policy (Ozturk, 2009; Apergis and Payne, 2010). However, very few studies investigate the energy-economy relationship on a city level. This paper focuses primarily on the urban understanding of the energy-economy nexus through a study of cities.

As recognised in many studies, the majority of the world’s population now live in cities, where quality of life and environmental concerns undermine all advantages associated with agglomeration economies (Grubler *et al.*, 2012). The pressures and potentials to find ways to reconcile economic growth, well-being, and the sustainable use of natural resources, will therefore be greatest in cities (Swilling *et al.*, 2013). Since cities each have different characteristics, understanding how an individual city functions may facilitate interventions for a smoother transition towards a sustainable city.

In order to ensure economic growth throughout the transition to sustainable cites, it is thus vital to understand the causality and dynamics between energy consumption and economic growth at a city level. A literature review was conducted to investigate the linkages and causality between energy consumption and economic growth, in order to explore how energy transitions can drive economic growth. The outcomes from the literature review led towards an understanding of the current state of the energy-economy nexus in cities. The outcomes are the discussed, and the paper rounds off with a conclusion and recommendations for practitioners in the field.

2. Energy-Economy Nexus

In general, mainstream economists neglect the idea that high energy prices can cause economic decline or stagnation. It is frequently argued that energy costs are small compared to other expenditures that make up GDP (e.g. consumer spending, which makes up about 70%), which makes them insignificant (Aucott and Hall, 2014; Heun *et al.*, 2017). This view ignores the importance of energy as a multiplier of economic growth and development. Energy is a domestic necessity and also a factor of production (enabling a variety of services such as transportation, heating, and food production), whose price directly affects the price of other goods and services. If the price of energy increases, almost everything costs more, and this ripples through the economy.

Mainstream economic thinking has not identified energy as a primary factor of production (Stern, 2011; Aucott and Hall, 2014; Heun *et al.*, 2017). Resource economists have developed models that incorporate the role of energy in the growth process, but these ideas remain isolated in the resource economics field (Stern, 2011). However, there is a lack of consensus on the causality between energy consumption-economic growth, and electricity consumption-economic growth (Ozturk, 2009). These conflicting results may arise due to different data sets, countries’ characteristics, variables used and different econometric methodologies have been used. However, an important conclusion on the relationship between electricity consumption and economic growth for the country-specific studies were drawn, which is that the causality is from electricity consumption to economic growth. Consequently, it is found that electricity is a limiting factor to economic growth and, hence, reductions in electricity supply will have a negative impact on economic growth (Ozturk, 2009).

2.1 Energy Cost Share

Recently, the impact of energy cost share on economic growth has received attention in the literature (de Wit et al., 2013). The components of energy cost share in a given time period (*CS*) are: energy type (*i*), energy price for each type (p_i), energy consumption rate for each type (Q_i), and GDP. The energy cost share for an economy at a given time *t* is calculated by (de Wit, Heun and Douglas, 2013):

$$CS_i = \frac{\sum p_{i,t}\, Q_{i,t}}{GDP_t}$$

Energy cost share proves to be a useful indicator of an economy’s energy expenditure, since it considers both the energy price for each type (p_i), and the energy consumption rate for each type (Q_i) in relation to the country’s GDP. It therefore gives a good indication of the energy investment in relationship to economic growth at a particular point in time.

However, there is an upper threshold to a countries’ energy cost share (Bashmakov, 2007). When the energy cost share rises above this threshold, recessionary pressures reduce the energy demand, thereby reducing energy prices, which in turn reduces the total energy cost share to its earlier (equilibrium) value (Heun and de Wit, 2012). Interestingly, there is only a correlation between energy costs, income levels and economic activity, when the energy affordability threshold is exceeded. Beyond the energy affordability threshold, economic growth becomes highly dependent on fuel expenditure.

A study of the economic growth (GDP) and energy cost share of US between 1950 and 2013 revealed an energy affordability of around 4% of GDP; since the energy cost share in the US is approximately 5% of GDP further economic growth is unlikely (Aucott and Hall 2014). Furthermore, the energy cost share of the US is likely to increase as the energy return on investment (EROI) for petroleum will continue to decline and prices will increase over the long term. However, this study used expenditures on primary fuel (coal, oil, natural gas and nuclear ore) to calculate energy cost share does not give an indication of the cost of energy to the consumer. Furthermore, primary fuel cost are changing as new methods of extracting energy are developed and governments heavily influence the price of energy through a range of financial instruments, such as subsidies, taxes and levies.

There are at least two ways that countries can lower their fuel cost share in the future- becoming more energy efficient and replacing fossil fuels with renewable energy options that have lower costs of production.

2.2 Energy Return on Investment (EROI)

EROI is an important metric as it accounts for costs expended to deliver energy from extraction to the consumer. EROI is defined as the ratio of gross energy output ($E_{gross,t}$) obtained from an energy production activity, such as drilling for oil, mining for coal, or building wind turbines, to energy input ($E_{input,t}$) for the energy production process during a period of time (*t)* (Heun and de Wit, 2012):

$$EROI_t = \frac{E_{gross,t}}{E_{input,t}}$$

By this definition, the break-even point for energy production is when EROI = 1. Thus a process with EROI > 1 is an energy source and a process with EROI < 1 is an energy sink (Heun and de Wit, 2012). Furthermore, for energy production processes, it is apparent that the higher the EROI, the more energy is supplied to society – this can be visualised in Figures 1 & 2.

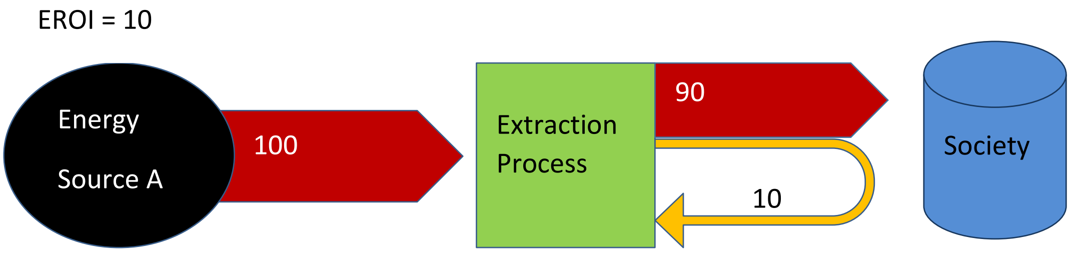

Figure 1: Energy Source with EROI = 10

Source: Adapted from Heun and de Wit (2012) and R. K. Roberts (2017)

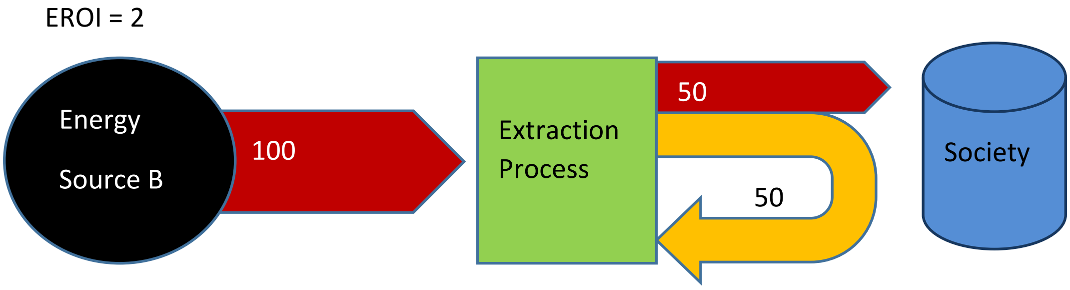

Figure 2: Energy Source with EROI = 2

Source: Adapted from Heun and de Wit (2012) and R. K. Roberts (2017)

As the EROI of energy sources decrease, the market price of the energy increases (King, 2011), and economic models have been developed in an attempt to predict the market price of energy, given an energy source’s EROI (Heun and de Wit, 2012). Since EROI has been shown to dictate energy prices, it is an important to energy policy and energy sources with the greatest EROI should be used when deciding on a country/city’s energy mix.

As oil supplies continue to become depleted, there is a tendency to extract energy from energy sources with a lower EROI. The EROI values for various energy sources can be plotted against the net energy efficiency in order to guide energy policy and energy developments (Murphy and Hall, 2011) - see Figure 3. The most important concept provided by this figure is that when EROI values decline below 10, the net energy provided for society decreases exponentially. Unless society reduces its reliance on fossil fuels, which have a rapidly decreasing EROI, the globe will move towards a “net energy cliff” (Lambert *et al.*, 2014).

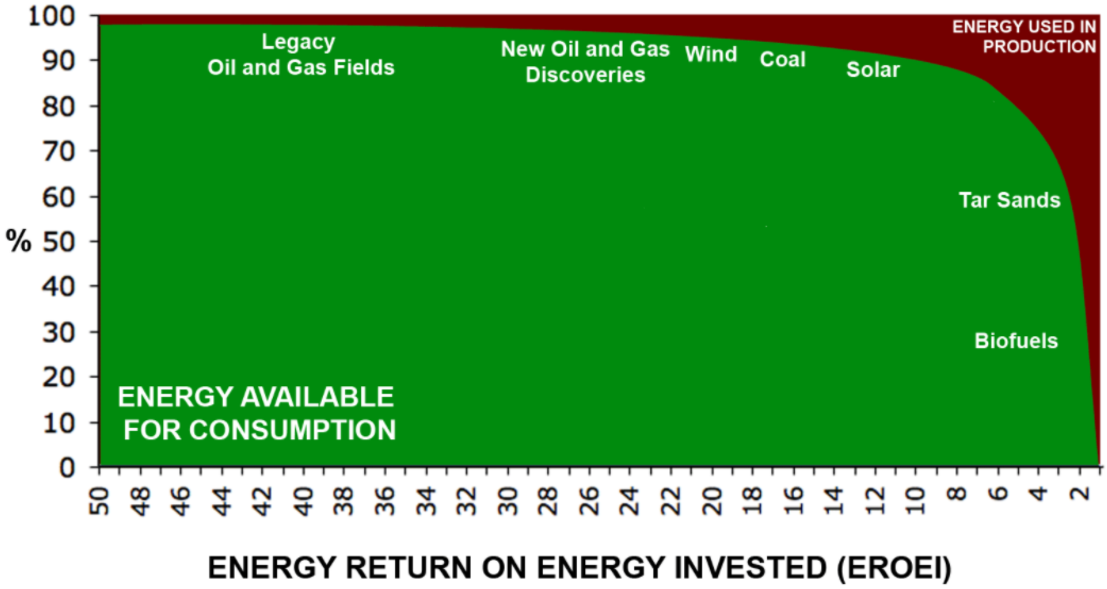

Figure 3: The Net Energy Cliff (Murphy and Hall, 2010)

A comprehensive comparison between world economic and net energy metrics has been carried out using data from 1978-2010 for 44 countries that contribute to 90% of global GDP (King, Maxwell, & Donovan, 2015). This revealed that the costs of energy are an important factor in economic growth; and global energy cost share is significantly correlated with the one-year lag of the annual changes in GDP (King et al. 2015). However, it is noteworthy that the correlation coefficients calculated in this study were mostly not statistically significant; which may have been due to a lack of accurate time series data available and the short time period in which this data has been recorded. An alternative explanation is that energy prices play little role in influencing economic growth – it is only when energy expenditure reaches an upper threshold, that it starts to restrain the factors contributing to economic growth such as labour and capital (Bashmakov 2007; Aucott and Hall, 2014). This also alludes to the use of critical energy cost share thresholds as being a more important metric than general correlation coefficients (Roberts, 2017).

It is important to note that these energy cost share thresholds may be different from country to country, depending on whether it is a net importer or exporter of energy, and will likely change with time. Establishing these thresholds, if any, and determining a correlation between economic growth and critical energy expenditures once these thresholds have been exceeded is of utmost importance since it indicates the level of investment in energy beyond which there will be little economic benefit. These thresholds can then be used to guide the expansion and mix of the national energy supply system, using a range of energy supply options with different EROI.

2.3 Energy Intensity

Energy intensity can be defined as “*the ratio of energy use to a relevant measure of activity or output*’’ (Schipper and Grubb, 2000), or the energy used per unit of gross domestic product (IEA, 2003). Fundamentally, a high energy intensity means a high cost of converting energy into economic growth (GDP); while low energy intensity implies a low cost of converting energy to economic growth (GDP). In other words, lower energy intensity means a higher amount of energy efficiency.

From the foregoing definitions, several aspects are important in understanding energy intensity in developing countries- the rapidly growing energy demand; the capital intensiveness of energy industry; the security of energy supply in terms of quality, reliability and continuity; and the overall economic development pathway of the country (Jamasb et al., 2005).

A review of the Human Development Index published annually by the World Bank demonstrates sufficiently that economic development is an urgent issue in developing countries. However, ample evidence shows that there can be no meaningful economic development without affordable energy (Priddle, 2002). Part of the underdevelopment issues in sub-Saharan Africa (SSA) has to do with energy scarcity. For instance, Nigeria, with a population of over one hundred and forty million people, can only produce about 1 600 megawatt (MW) of electricity, while Ireland with a population of about four million people produces over 4 000 MW of electricity (Fufore, 2012). It is no wonder then that, while Ireland ranks 5th on the United Nations Development Program’s (UNDP) Human Development Index (HDI), Nigeria is ranked 158th (UNDP, 2007).

The trend in the structure and intensity demand in developing countries seems to follow the same pattern as developed countries historically, where energy use and intensities grew significantly with economic growth during the industrialisation era, but began to decline considerably as the economies moved to secondary and tertiary industries (Metcalf, 2008; Shipper et al., 1993; Zhang et al., 2009). However, energy use continued to grow until after the oil crisis when “*a new phenomenon known as ‘decoupling’ has been observed”* (Stage, 2002) where energy use is growing at a much slower rate than economic growth. This is because of a shift to tertiary industry and higher prices have promoted the use of energy efficient technologies (Stage, 2002). These studies indicate that energy intensity first increases as a consequence of expanding economic growth and development, but consequently falls as a result of a shift to a services-based economic structure (Medlock III and Soligo, 2001).

One of the major means of reducing greenhouse gas (GHG) emissions emanating from fossil fuels is to cut down the energy used per unit of economic activity (efficiency). Therefore understanding the drivers of the intensity of energy use is an important step from an energy policy making viewpoint, since it is a measure that combines energy consumption with economic output (Zhang et al., 2009: 5477). It is similarly imperative for the policy makers to comprehend how energy demand will change under situation of structural change in the economy (Markandya et al. 2006). An emerging pattern of energy intensity and economic growth can be seen from a historical perspective of development. When industrialisation began energy intensities and energy consumption increased rapidly with economic growth. However, later on the path of industrialisation, energy consumption was reduced while economies continues to grow as a result of gradually switching from primary to secondary and tertiary industries. There are some apparent anomalies to this trend in countries like Philippines, Brazil, Colombia and Argentina, where energy intensity is found to be “superficially” low compared to the level of economic growth. This phenomenon can be explained by examining the disparity between the rich and the poor. A large gap between the two social classes means that rich people drive the GDP of the country up, while energy consumption (especially the one contributed by lifestyle choices) remains low since most of the people are poor and therefore unable to consume a significant amount of energy enough to tip the balance between GDP and national energy consumption (Suehiro, 2007).

2.4 Decoupling

The term 'decoupling' has been promoted as a way to describe the efforts to break the causal link between economic prosperity with the depletion of finite resources and degradation of environments (UNEP, 2011; Swilling *et al.*, 2013). The focus of sustainable development is therefore to decouple economic growth from the increasing use of energy and material resources. Global economic production and consumption is now concentrated in cities, with 80% of global GDP now associated with cities. The second point is that a second major wave of urbanisation is underway: since 2007 the majority of the world’s population of over 7 billion people has been classified as living in urban settlements. The third departure point is that global resources consumption is concentrated in cities. By the year 2005, approximately 75% of global energy and material flows were consumed in cities, which covered just 2% of the land. Given predicted growth of cities and the important role that cities will have in shaping economic growth, there is an urgent need to understand how this growth can be achieved in a sustainable manner.

One approach is to decouple economic growth from resource use and environmental impacts (UNEP, 2011). Resource decoupling (strong decoupling) or 'dematerialisation' involves reducing the rate at which primary resources are used per unit of economic output. In other words, resource decoupling refers to increasing economic output while decreasing resource use. Impact decoupling (weak decoupling) means increasing economic activity while decreasing negative environmental impacts; such as pollution, greenhouse gas emissions, and biodiversity loss. Both are illustrated in Figure 4.

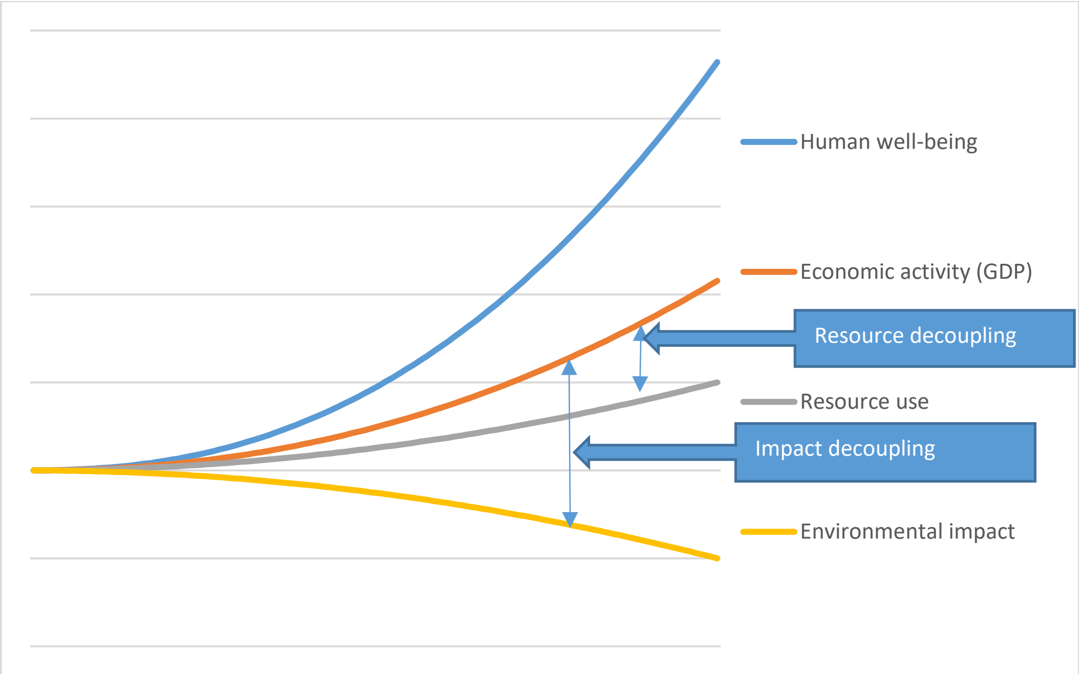

Figure 4: Two aspects of decoupling

Source: Adapted from UNEP (2011)

Energy is arguably the most important resource for economic development (Grubler *et al.*, 2012), since the vital urban infrastructures all depend on energy: treatment and supply of water; the disposal and treatment of wastes; transport and communication systems; building and construction; supply of food, materials, medicines and chemicals; and the energy supply itself. Understanding the relationship between energy consumption and economic growth is fundamental to decoupling economic growth from resource use (resource decoupling), while an increased understanding of the environmental impacts of energy supply options is needed for impact decoupling.

Furthermore, the concept of ‘absolute decoupling’ vs ‘relative decoupling’ is crucial to monitor the environmental pressures of an economy. Figure 4 has shown that decoupling occurs when the growth rate of an environmental pressure is less than that of its economic driving force (e.g. GDP) over a given period. Absolute decoupling is said to occur when the environmentally relevant variable is stable or decreasing while the economic driving force is growing. Decoupling is said to be relative when the growth rate of the environmentally relevant variable is positive, but less than the growth rate of the economic variable.

Decoupling indicators, like all other types of indicators, shed light on particular aspects of a complex reality but leave out other aspects. For example, the decoupling concept lacks an automatic link to the environment’s capacity to sustain, absorb or resist pressures of various kinds (deposition, discharges, and harvests). In the case of renewable natural resources, a meaningful, interpretation of the relationship of environmental pressure to economic driving forces will also require information about harvesting rates compared to renewal rates.

3. Sustainable Cities

Sustainable cities have been included amongst the 17 Sustainable Development Goals (SDGs)[1], and the New Urban Agenda of 2016 elaborates how sustainable development should manifest in cities (Swilling *et al.*, 2017). The importance of analysing our urban energy systems has thus gained significant attention recently (Grubler *et al.*, 2012; Swilling *et al.*, 2013). This section looks into some of the key focus areas that are expected to have considerable effects on the urban energy-economy relationship, but whose influence is uncertain, namely: energy efficiency, the importance of local governments, and finally, the unrecorded economy (Karanfil, 2008; Warr, Schandl and Ayres, 2008; Kohler, 2013; Aucott and Hall, 2014).

Whether a city can be truly sustainable is debatable. This is due to the varying priorities with which cities contend, the manner in which their boundaries are delineated, and the challenges in identifying and measuring appropriate indicators of urban sustainability (Currie et al., 2017). In addition, the vision of a sustainable city as a utopian entity is potentially unhelpful, as it may impose a contextual or unrealistic development pathways on the city (Campbell 1996). A sustainable city that externalises its resource use and impacts to locations outside its boundaries cannot be considered sustainable from a multi-level perspective. Arguably, cities are not either sustainable or unsustainable, but rather encompass various socio-economic and socio-ecological processes “*that negatively affect some social groups while benefiting others*” (Allen, 2001). Therefore, political considerations are important to address the inherent trade-offs or contradictions in addressing the social, environmental and economic aspects of sustainability simultaneously.

There is also a need for urban energy policy to focus primarily on demand management, such as energy efficient buildings, structuring urban form and density conductive to energy efficient housing forms, high-quality public transport services, and the integration of urban energy systems. This demand-side focus at the urban scale represents a paradigm shift compared to the traditional, more supply-side energy policy focus at the national scale; and offers opportunities for a more efficient use of energy in urban environments may have a considerable effect on the economy of the city (Grubler *et al.*, 2012).

3.1 Energy Efficiency

Increasing energy efficiency has been broadly considered as the most cost-effective way to mitigate greenhouse gas emissions and is one of the most important ways to reduce the threat of increased global warming (European Parliament, 2009; IPCC, 2007). Without efficiency improvements since 2000, the world would have used 12% more energy than it did in 2016 – equivalent to adding another European Union to the global energy market (IEA, 2017). Energy efficiency is the “*least expensive, most benign, most quickly deployable, least visible, least understood, and most neglected way to provide energy services*” (Lovins, 2005).

This is most important in countries rapidly building infrastructure, where efficiency opportunities lost now lock in wasteful energy use for decades. As IEA member nations’ absolute energy use shrinks from its 2007 peak, developing countries’ rising share of global energy use offers important opportunities to leapfrog to the best technologies, in which they could even seek and achieve market dominance (Lovins and Browning, 1992; Cagno *et al.*, 2013; IEA, 2017).

[1] https://www.un.org/sustainabledevelopment/sustainable-development-goals/

With energy efficiency as its cornerstone and needing its pace redoubled, climate protection depends critically on seeing and deploying the entire efficiency resource. This means extending modern net-zero or net-positive and deep-retrofit building-design philosophies—examples of integrative design—into industry, vehicles, mobility, and their links to IT and urban form; broadening our climate-change-mitigation analytic framework from components or devices to whole systems; and replacing theoretical assumptions about efficiency’s diminishing returns with practitioners’ empirical evidence of expanding returns (Lovins, 2018).

3.2 The Importance of Local Governments

There is growing global, national and local awareness of the role of urban and local management as being key to many areas of sustainable energy development and climate change mitigation. If a municipality is going to have an impact on transition to a green economy in the area under its jurisdiction it must influence change amongst its broader constituency – the residents and businesses of the city or town. There are principally two ways of influencing the behaviour of citizens and businesses: through regulations and policies, and by providing support and information (Sustainable Energy Africa, 2017).

A green economy is defined as one that results in “*improved human well-being and social equity, while significantly reducing environmental risks and ecological scarcities*” (UNEP, 2010). In its simplest expression, a green economy is low-carbon, resource efficient, and socially inclusive. In a green economy, growth in income and employment are driven by public and private investments that reduce carbon emissions and pollution, enhance energy and resource efficiency, and prevent the loss of biodiversity and ecosystem services. While the idea behind a green economy is spreading fast, much of the current discussion centres on national developments (ICLEI, 2012).

Due to an increasingly active network of local leaders, supported by organizations such as ICLEI - Local Governments for Sustainability – a consensus is emerging that the notion of “*think global – act local*” is imperative to find sustainable solutions to the challenges of resource scarcity and climate change (ICLEI, 2012). When pursuing a sustainability agenda, local governments have certain ‘tools’ at their disposal, such as governing by authority (e.g. acting as a regulator); governing by enabling (e.g. promoting certain policies towards relevant stakeholders such as a national ministry); governing by provision (e.g. giving financial support to specific activities such as the purchase of solar water heaters); and self-governing (e.g. being a role model in energy efficiency projects in public buildings) (ICLEI, 2012).

Each city is unique, so combining analysis on the global level with constant ‘deep dives’ into local and regional strategies can assist cities to find the most suitable individual strategies. Collaboration with higher levels of government is essential if cities and networks of cities are to overcome regulatory barriers and access funding. It is thus crucial that higher levels of government support city-level innovation for resource efficiency (Swilling *et al.*, 2017).

City governance has a central role to play in managing energy consumption and GHG emissions. City governance can incentivize energy efficiency, and promote renewable energy use and public transport. Indirectly they can influence city energy use through urban planning and economic development (Sustainable Energy Africa, 2014).

3.3 Unrecorded Economy

The definition of an unrecorded economy is that of an underground or shadow economy, which is the "*market-based production of goods and services, whether legal or illegal that escapes detection in the official estimates of GDP*" (Smith, 1994). Developing countries have the highest unrecorded economies accounting for 44% in African economies and 39% in Latin American countries. Concerning transition and developed countries, the unrecorded economy is estimated to account for 20% in Middle Eastern and Eastern European countries and 12% in OECD (Organisation for Economic Co-operation and Development) countries (Gërxhani, 2004). Thus, the investigation of the linkage between energy consumption and the official economy may not give reliable results in such countries. It would appear that a country's energy input is not transferring to economic output due to the scale of the unrecorded economy.

However, energy input may not be an essential factor of production in the *unrecorded* economy (Karanfil, 2008). This is alleged to be due to unrecorded economic activities having low energy inputs, such as peddling or hawking. These results may not be a true reflection of the situation, since estimating energy demand is a difficult task in informal settlements, as households that do not have legal land tenure are not entitled to public services provision (Payne, 2001). Unrecorded economies should be included in future energy-economy studies, especially in developing countries, in order to build comparative research to ultimately form a generalizable conclusion (Karanfil, 2008). The causality between energy consumption and GDP has been of much interest to researchers for decades, even though there is yet to be a consensus on the direction of the causality. Studies are divergent regarding the direction, ranging from unidirectional, bidirectional and no direction at all.

4. Conclusions and recommendations

Previous literature that has compared energy consumption to economic growth shows that the causality between energy and economic growth is unclear. However, many studies using energy metrics, such as energy cost share, show a strong link between energy and the economy. These studies provide valuable information, but fail to provide a complete picture of the dynamics between energy and the economy needed by policy-makers to transition towards a green energy strategy.

Understanding the energy-economy nexus in cities of developing countries will be key to enabling effective mechanisms to transition to sustainable development. There are several challenges to this area of research; such as data scarcity at the city level in cities of the global South, and particularly in African cities (Currie, 2015) and difficulty in tracking informal, unregulated, illegal or decentralized energy systems (Kovacic *et al.*, 2016; Currie, Musango and May, 2017).

Energy cost share proved to be a useful indicator of an economy's energy expenditure. It was found that when energy cost shares rise above a certain threshold, recessionary pressures reduce energy demand. EROI was found to dictate energy prices, and it is therefore important to energy policy; energy sources with the highest EROI should be chosen when deciding on a country's energy mix. Energy intensity was identified as an important metric for cities to track the energy efficiency of their economies. Three key focus areas were identified that are expected to have considerable effects on the urban energy-economy relationship, but whose influence is uncertain; namely-energy efficiency, the importance of local governments, and finally, the unrecorded economy.

In order to decouple economic growth from resource use and environmental degradation, cities need to switch to energy efficiency policies and renewable sources of energy. Stronger policy development and implementation is essential if the current level of efficiency gains is to be maintained or accelerated.

4.1 Ongoing Research

The ongoing research is to perform case studies on different cities to evaluate the relationships between individual economies and their energy consumption. This would reveal if different patterns exist for different regions, and whether a city’s economic and energy profile influences the causality between energy consumption and economic growth. The ongoing research further involves evaluating how different policies and crises (natural disasters, supply shortages etc.) have affected the energy-economy relationships of cities. Investigating whether changes in energy prices have affected the energy-economy relationship is also fundamental to the ongoing research. Whether the changes in energy prices have an influence on consumer habits and practices, and how this impacts the total energy consumption of a city or the economic growth of a city, also forms part of the ongoing research. The findings of this research will be shared during the author’s oral presentation at the 2018 ISDRS conference.

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