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A comparison of energy systems in Birmingham, UK, with Masdar City, an embryonic city in Abu Dhabi Emirate

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ABSTRACT

Energy is a vital resource in modern life. With increasingly limited availability of traditional energy resources, e.g., oil, coal and nuclear, together with environmental concerns, there is raised awareness that energy needs to be both used more efficiently and generated in line with thinking on sustainability. Ready access to 'clean' energy is essential if we wish to maintain our current way of life without compromising our wellbeing or the carrying capacity of the planet. This paper aims to analyse the differences and similarities in energy supply and demand between two very different cities. Masdar City, founded in 2008, is a dynamic new Middle-Eastern city being built in a desert environment. Its aim is to be the most sustainable city in the world and offers an exciting opportunity to provide unique insights into the application of different innovative technologies as 'new-build' within an urban environment. Birmingham is a well-established post-industrial city that has evolved over fourteen hundred years. It was one of the fastest growing cities in 19th century England (Popp and Wilson, 2009) [1]. To do this a material flow analysis approach has been adopted to provide a framework for the study. The energy-related opportunities and mutual benefits that each city can gain from the experiences of the other are explored and five emergent issues are identified: innovation and experimentation, lock-in, balance, resilience and governance. This work shows how a greater understanding of common issues can lead to more sustainable, resilient and robust cities, able to face the challenges of the next 50 years.

Contents

1. Introduction

Energy is a vital component in modern-day life and is responsible for the survival (food production, cooking, heating, cooling, water, transport of essential resources) and day-to-day activities (mobility, lighting, machinery, equipment,

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communications, entertainment) of billions of people across the globe. Unfortunately, the current global resources supplying this energy demand are on the decline and, according to BP, we will have consumed all known global oil and gas reserves by around 2066. Coal is more abundant, but it too is predicted to run out by around 2126 [2]. By 2050, nuclear and renewable energy are expected to account for just under 30% of energy supply, with 40% still supplied by coal and the remaining 30% from oil and gas [3]. At the same time, there is an unprecedented and increasing demand on such resources, especially from developing countries [2]. Notwithstanding the contributions of shale gas and tight oil, the common concern of rising costs of energy and a greater awareness of the need for sustainability has spurred many nations into action to address dwindling resource supply.

Across the world there is an increasing awareness of rising CO_2 levels and a changing climate. This has led many countries to adopt strict limits on the amount of CO_2 emissions permitted though these vary in the degree of legislation, enforcement and penalties.

In the UK, the Climate Change Act (2008) states that: “It is the duty of the Secretary of State to ensure that the net UK carbon account for the year 2050 is at least 80% lower than the 1990 baseline” [4]. The European Union has endorsed this objective arising from the Kyoto Protocol, which came into force in early 2005 [5]. This legislation has also fed through to the local level with many UK Councils, including Birmingham City Council (BCC), developing their own carbon reduction plan with even more ambitious targets in terms of timeframes [6]. Renewable energy plays a major part of the Government's plans for decarbonising the UK national electricity grid and for a reduction in the use of fossil fuels in the UK's energy supply [7].

At the same time, over in the Middle East, one country taking a lead in the development of sustainable energy, perhaps surprisingly given its dependence on and access to oil and gas, is the United Arab Emirates (UAE). There has been phenomenal growth in renewable energy initiatives in this region over the last 10 years, allied to a surge in development combined with generous government funding. The Abu Dhabi Emirate has been particularly keen to embrace the concept of sustainability and has produced an economic vision for 2030 which encompasses it [8]. This vision adopts the ideology of sustainability originally proposed in the Brundtland report [9] by addressing the quality of the public space and emphasising the importance of community identification and social links alongside the importance given to the development of infrastructure. In addition, the government of Abu Dhabi has a target of 7% of renewable energy capacity by 2020 [10], which equates to around 1500 MW [11]. However, since the economic collapse of 2007/2008, expansion has occurred at a slower pace. Some projects have been reduced in scale or stopped, yet, in spite of this; ambitious plans are still being achieved.

Masdar City was established with the aim of being an exemplar of sustainable energy development and to act as a showcase for new technologies. US$15 billion have been committed to the project, along with more than US$1.7 billion of equity in renewable energy projects worth more than US$6.4 billion in Abu Dhabi and around the globe, including the London Array and solar projects in Spain [10]. At its heart is the Masdar Institute, an education establishment with 337 students and the global headquarters building for the Siemens electrical company [10].

Two key questions posed by the issue of diminishing fossil fuel supplies are: what are the alternative energy supply options and how successfully can renewable energy infrastructure be implemented within an urban environment? In addition, there are concerns about the sustainability of many cities, particularly with growing populations, so fuel efficiency and the minimisation of energy use is also of interest. To try to address these questions and to highlight work that has been carried out in the Arabian eco-city, Masdar City, which aims to be the most sustainable city in the world, this paper investigates the similarities and differences between the existing energy systems in the embryonic city, with Birmingham, a well-established post-industrial city in northern Europe. The approach adopted follows a Material Flow Analysis (MFA) whereby the inputs and output flows of the system are quantified and placed in the context of each city. Five core issues are identified from this work: innovation and experimentation, lock-in, balance, resilience and governance. These are explained in more detail within the paper.

The aim of this paper is to explore energy supply and use in two very different cities – Birmingham, UK and Masdar City, UAE – with very different histories, economies, climates and cultures, and to show how developments in both can lead to a common understanding about the most efficient use of energy. To assess the energy systems of the two cities and to compare them, a Material Flow Analysis (MFA) approach has been used. This approach builds on the theory of Urban Metabolism and its application to city resource flows. Urban Metabolism and Material Flow Analysis (MFA) are briefly explained in Section 2 followed by a comparison between the two cities in Section 3 and their associated energy use. We assume no major changes over the short-term. Section 4 discusses the energy strategies within the context of the two cities, while the conclusion (Section 5) includes proposals for how this understanding will help Masdar and Birmingham to be more resilient, robust and sustainable over the next 50 years and beyond.

2. Methodology

2.1. Urban Metabolism and Material Flow Analysis (MFA)

Urban Metabolism examines the resource flows into and out of a city and considers them from a biological point of view. Material and energy flows are the inputs, waste and emissions are the outputs, and buildings and infrastructure are the stock. The city is viewed as a living organism which is constantly restructuring and developing. The term is attributed to Wolman [12] who originally introduced the method to study air and water pollution in American cities, and has been used by numerous authors since, across many disciplines [13–15]. For a full selection of reviews on the topic see [16–18].

Material Flow Analysis (MFA) is a methodology that has arisen out of Urban Metabolism studies. It was originally developed by Paul Brunner [19] and quantifies flows and stocks in a system across space and time. This technique provides a framework in which production, stocks and consumption of energy can be assessed for each city. This paper focuses on the single resource of energy for a given year (2012) though some more recent data (up to 2015) are also presented. Birmingham is bounded by its municipal boundary and Masdar by its city plan area. However, the energy consumption of each city is considered in its respective country's context. Energy consumption is expressed in terms of mass (Mtoe, Million tonnes of oil equivalent) at the country level and in terms of electrical energy (kWh) at the local level.

Energy consumption data have been extracted for each city, as well as energy production and consumption data for their respective countries (United Arab Emirates and the UK). These data were then compared and assessed within the context of each country taking account of the different climates, pricing systems, energy efficiencies and type of energy used by different sectors (e.g. domestic, industry, transport, etc.). The approaches to sustainability and local schemes were also compared as well as an assessment of the resilience of each city.

Table 1
Summary of the key characteristics of each city.

Subject	Masdar City		Birmingham Metropolitan District
	Current (2015)	Projected by 2030 (estimated completion date)	
Latitude/Longitude	24°25′45″N 54°37′6″E		52°28′59″N, 1°53′37″W
Climate	Subtropical		Warm temperate
Population (people living in city)	570 [20]	40,000 [23]	1,092,300 (2013) [29]
Population density (people/km^2)	95	13,000–16,000 [84]	4012 [28]
People aged 16–64	n/a		699,700 (2013) [29]
Commuters	n/a	50,000 [23]	196, 089 (In); 83,495 (Out) [64]
People employed in the city	1320		426,300 [29]
Area of city (km^2)	6	6	268

3. Comparison between Masdar City and Birmingham

3.1. Key facts: Masdar City and Birmingham

Table 1 provides a summary of the key characteristics of each city including its population, population density, geographic area and demography. The population of Masdar consists of staff and students at the Masdar Institute and employees of Siemens and a few other companies. For 2015, the daytime population of Masdar consists of graduates and students at the Masdar Institute (around 570 people) [20], as well as employees of Siemens (800 people (estimated 528 people in 2014)), IRENA (90 people), Masdar employees in Masdar City (210), other companies such as Mitsubishi and General Electric, and with the staff at the Masdar Institute (220 people) [20] this equates to 1890 people which is further confirmed by [21]. Many of these people currently commute to Masdar City, with Masdar Institute students making up the bulk of the residents of the city. This is expected to change as more residential buildings are built. For 2014 the population was estimated to be 1618 people. The contrasts between the two cities are evident in their size, populations, density of people and climate.

3.2. History: Masdar City and Birmingham

Masdar City (24°25′45″N 54°37′6″E) is a large-scale mixed use development which lies 17 km south-east of the centre of the city of Abu Dhabi, in Abu Dhabi Emirate, one of the seven United Arab Emirates (UAE). It is the first city in the world to be designed to be “zero-carbon” and “zero-waste”. It was established in 2006 through the Mubadala Development Company owned by the Abu Dhabi Government with a view to building “the world's most sustainable city” of 40,000 people with 50,000 commuters covering 6 km^2 and producing economic development and diversification in the Emirate. It was due to be completed in 2016, but with the global economic downturn this led to a revised completion date of 2025 [22]. The city is designed to encourage walking, with any nearest public transport link being within a maximum walking distance of 350 m. Residents and commercial tenants can walk or use public transportation for all their needs within Masdar City [23]. Additionally, Masdar City will be linked to Abu Dhabi City's upcoming public transportation options of the LRT (light rail transport) which covers the outskirts of the city and the Metro light rail system within Abu Dhabi City, some of which may be underground [24]. Masdar City's buildings are only permitted to be up to five stories high, and are built on narrow streets, with rooftops covered with solar panels and street-level “solar canopies” providing shade. The shaded paths and narrow streets are designed to create a pleasant environment in which to walk in Abu Dhabi Emirate's hot climate. The City is expected to consist of 10 neighbourhoods constructed one at a time over seven phases and building on previous experience through each phase. The city is to be surrounded by a wall to protect it from the desert winds, as well as from the effects of dust and noise arising from the nearby Abu Dhabi airport.

The first six buildings of the Masdar Institute of Science and Technology included three residential buildings, two laboratory buildings and a Knowledge Centre – a total of 35,000 m^2 of gross floor area. Construction of the second phase of the Masdar Institute is now complete, which more than doubles the size of the Institute to approximately 80,000 m^2 with new student accommodation, flats, science and sports facilities together with a number of retail outlets [25]. The 10,000 m^2 Incubator Building, the first commercial building in the city, is also now complete with companies like GE, Mitsubishi Heavy Industries, Schneider Electric and more than 50 small and medium-sized enterprises (SMEs) taking office space. In addition, the Siemens Middle East Headquarters Building (23,100 m^2) currently houses 800 employees with a further 700 expected to join them over the next few years. These buildings represent projects that are tripling the size of the city, from 35,000 m^2 to approximately 110,000 m^2. The building for the new Masdar HQ and the International Renewable Energy Agency (IRENA) was completed in Jan 2015. The staff for this building, together with planned residential projects, will further increase the city population. In 2013, Masdar City had an estimated population of around 1000, consisting mostly of students [26] but taking into account new employees at Siemens some of whom are likely to be day-time commuters into the city this has now risen to just under 2000.

The future of Masdar City is, however, beginning to look more uncertain with many office blocks within the city unoccupied, and large areas of undeveloped land (only 5% of the total city area of 6 km^2 is built on) [21]. There are also concerns that some existing companies may move on to more profitable locations (in terms of tax, cost of living, proximity to markets etc.). Furthermore, any people employed in these companies are not emotionally bound to the city through home ownership, as many rent their accommodation [27].

Birmingham (52°28′59″N, 1°53′37″W) is in the English West Midlands and is the UK's second city, in terms of size, after London. It grew during the Industrial Revolution mostly due to its easy access to coal, iron, limestone and water, and became famous for its iron and steel-making. Birmingham Metropolitan District covers an area of 268 km^2 with a density of 4012 people/km^2 [28]. It is home to just over a million people with 426,300 people employed in the city [29]. Birmingham has a young population, with 23% of its population under 16, and is multicultural with 42% of its population from a non-UK background [30]. The city is 300 m above sea level and has no major rivers. However, there are three small rivers – the Cole, Tame and Rea – and six major canals covering around 161 km [31]. Despite its industrial past, Birmingham has 3200 ha of parkland [32] and was the first UK city to become a ‘biophilic’ city [33].

Established around the early 7th century [34], Birmingham prospered with the development of many industries linked to metal working. During the 18th century, as part of the Midlands Enlightenment [35], it was at the forefront of worldwide developments in science and technology and grew into a major manufacturing and engineering city – in 1791 it was acknowledged to be "the first manufacturing town in the world" [36] and was one of the fastest growing cities in 19th century England [1]. During the 20th Century it became renowned for car manufacturing: its Longbridge car plant opened in 1905 and by the 1960s became the largest in the world, employing around 250,000 workers [37]. However, during the 1970s and 1980s, Birmingham's manufacturing base declined such that today its economy is led by the service sector, which, in 2013, accounted for 86% of Birmingham's 416,900 employees. The city is the largest UK centre for employment in public administration, education and health (161,800 people), and in 2008 was the fourth-largest centre for employment in financial and other business services after London, Leeds and Glasgow, with 109,700 people employed in this sector [29]. In 2012 it was ranked as a "beta minus" world city, along with Abu Dhabi, by the Globalisation and World Cities Research Network [38,39] – an important world city instrumental in linking its region or state into the world economy.

3.3. Energy context: Masdar City and Birmingham

To fully understand the energy challenges faced by Masdar City and Birmingham it is important first to compare the current energy production and consumption in both Abu Dhabi Emirate and the United Arab Emirates, with the UK situation.

The population of UAE is just under 9 million people [40] against the UK's 63.7 million people [41]. In 2013, Abu Dhabi Emirate had a resident population of 2.4 million people of which nearly 80% were expatriates [42]. Many of these expatriates (around 63%) live in the Abu Dhabi region (1.24 million people) along with 263,207 Emirati citizens. Abu Dhabi city has a population of 967,655, again with more than three times as many expatriates (77%) than resident Emiratis (23%) [40].

Abu Dhabi Emirate's economy is heavily dependent on the production and selling of oil and liquid natural gas, with petroleum royalties and tax income accounting for 93% (2013 estimate) of Abu Dhabi Government revenues [42]. In 2013, the total production of Abu Dhabi Emirate natural gas was 78,047 million cubic metres (2,756,207 million cubic feet) of which 16,001 million cubic metres (565,062 million cubic feet) was used in its power stations to generate electricity (52 TW h in 2013) [42] for the domestic market and the desalination of water. Consumption exceeds production, so gas is also imported from nearby Qatar via an undersea pipeline (just over 23,590 million cubic metres (833,099 million cubic feet) [43]). In addition, the UAE has embarked on a nuclear programme with two nuclear power stations underway and two more planned. These are due to be completed by 2020 with a combined capacity of 5.6 GWe [44].

Natural gas is the main fuel (99.85%) used to generate electricity for the water and electricity industry in the Emirate of Abu Dhabi with other fuels such as crude oil, gas oil (diesel) and fuel oil used to power the remainder [42]. A considerable amount of the electricity generated is used in the desalination of water with more than 90% of desalinated water produced in combined cycle electricity and water plants powered by gas, resulting in one third of the Emirate's CO_2 emissions (29.6 $MtCO_2$ in 2013) [42,45]. Perhaps not surprisingly the transport sector dominates oil consumption with other final consumers and the domestic sector using most electricity. A small amount of coal (around 2 Mtoe) is used by industry and some oil (2 Mtoe) in non-energy use. The total amount of all types of fuel consumed for the five economic activities is around 31.4 Mtoe, of which natural gas accounted for about 80% [46]. The percentage of fossil fuels used across different economic sectors in Abu Dhabi Emirate is shown in Fig. 1. The

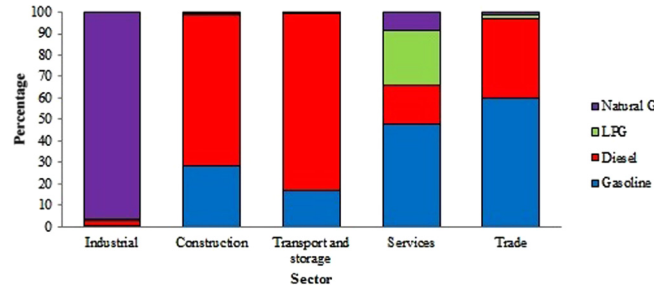

Fig. 1. Percentage of fossil fuels consumed by economic activity (2011) for the Emirate of Abu Dhabi [46].

classifications used here are summarised in the Annual Environmental Survey [46] which were in turn derived from the International Standard Industrial classification [47]. Fig. 1 highlights the importance of natural gas for industry (especially electricity production and desalination), and diesel fuel in construction (70%), as well as transport and storage (85%). Gasoline used in this context is equivalent to petrol. It is particularly important in the Services (just under 50%) and Trade (60%) sectors.

Masdar City has been developed against this backdrop with the intention of moving away from a fossil fuel-driven economy towards a more sustainable future based on renewable energy. When initially conceived, Masdar aimed to be a zero carbon city (as well as zero waste), although this ambitious target was replaced with that of being the world's most sustainable city in the face of anticipated difficulties in achieving this target. Nonetheless, the city's buildings and infrastructure are being planned and designed with energy-efficiency as the main objective.

At the same time, the UK's economy has becoming increasing dependent on imports, although it continues to be a large exporter of oil and natural gas. In 2013, the country produced and imported around 292 Mtoe of energy annually, consumed 150 Mtoe (51%), experienced transmission/distribution losses of 64 Mtoe (22%, mostly from coal and gas fired power stations) and exported around 79 Mtoe (27%).

Comparing the current energy production and consumption in the United Arab Emirates as a whole with the UK situation (Table 2), two facts immediately become evident; the huge amount of crude oil produced by the UAE (around 4 times that of the UK and 12% of Middle East production) and the large amount of refined oil products produced by the UK (10% of Europe's production) compared with the UAE (around 3 times greater).

From Table 2 it can be seen that UEA is a net exporter of energy, mostly through its crude oil production, whereas the UK is a net energy importer. However, the UK is an important provider of crude oil for Europe, supplying a quarter of production. Both countries provide 10–11% of their energy production to their region (the Middle East for the UAE and Europe for the UK). In addition, both the UEA and UK import natural gas as their consumption exceeds domestic production and continues to rise. The total energy consumption in the UK is around three times higher than in the UEA, due mostly to its higher population, its more northern climate (hence heating demands) and its high consumption of coal, crude oil and refined oil products relative to the UEA. However, per capita, the UAE consumes 7.3 toe per person compared with the UK citizen's consumption of 3.0 toe. In terms of resilience, a balance between imports and exports is helpful, although the fact that both countries are reliant on the import of natural gas makes them potentially vulnerable to geopolitical (e.g., supply and price) changes, in the short-term at least. Current reliance on fossil fuels makes the aspiration for a move towards far more sustainable states in 2027 and 2050 a challenge, and demands a shift towards greater flexibility in energy supply.

Table 2
Total primary production (quantity of natural resources extracted or produced), balance of trade (exports minus imports; net exporter is negative) and total energy consumption (balance of production, external trade, and stock changes) for the UAE and UK. Source: [48].

2013	Total energy (Mtoe)		Natural gas (bcm)		Electricity (TW h)		Crude oil production (Mt)		Refined oil products (Mt)		Coal/Lignite (Mt)	
	UAE	UK	UAE	UK	UAE	UK	UAE	UK	UAE	UK	UAE	UK
Production	210	109	54	38	106	356	162	41	28	66	0	13
% ME[a]/Europe	11	10	10	13	11	9	12	25	7	10	0	2
Balance of trade	−121	93	12	39	−9	14	−129	25	1	2	3	49
Consumption[b]	71	190	66	77	85	323	24	65	15	56	3	59
% ME/Europe[c]	10	10	15	14	10	10	7	10	5	10	17	6

Note the total energy value is in Mtoe.

[a] ME: Middle East.

[b] For crude oil production, consumption is input to refineries Source: [47].

[c] %ME/Europe is percentage of the UAE value of the total Middle East value and the percentage of the UK value of the total European value respectively.

Other factors that need to be considered with regard to energy use in the two cities include the cost of living, as well as the cost of energy itself (in terms of both generation – including extraction – and its cost to the consumer). In the UK, consumers are charged Value Added Tax (5%) on their energy and there is also a climate change levy for industry and public services (subject to certain exemptions, e.g. if combined heat and power is used). In addition, the UK government imposes a fuel tax on all petrol and diesel purchased (currently 58 p per litre) as well as other fuels (e.g. aviation fuels, biofuels, etc., with varying rates). The cost of living in Abu Dhabi compared with Birmingham is lower on average, with the cost of utilities being around 67% cheaper in Abu Dhabi city, the cost of transportation being 73–83% cheaper than Birmingham, and the cost of petrol being 35 p per litre compared with £1.12 in Birmingham. The average monthly disposable income after tax is £2201 in Abu Dhabi compared with £1559 in Birmingham [49]. According to the World Bank, in 2011 the GDP per capita based on purchasing power parity was £26,014 for the UK and £43,873 for the UEA. People in Abu Dhabi, including Masdar city, pay very low utility bills (0.5 p/kW[1] for local residential users and farmers rising to 2.7 p/kW for non-UAE nationals and non-residential users in 2010) and have cheap fuel for their vehicles, so there is little financial incentive to save energy. In 2010, energy consumption in Abu Dhabi was 12.68 t per capita (82% of energy consumption is from natural gas [46]) compared with 1.53 t per capita in Birmingham (2012 data) [50]. The Abu Dhabi Government is aware of energy wastage and is beginning to take steps to improve this situation, with increases in the latest electricity tariff [51]. However, these increases are mostly aimed at non-nationals who now face a rate of 5.7 p/kW (the locals pay 1.0 p/kW), although both these rates are well below the average rate of 15 p/kW paid by a UK citizen [52]. Industry rates range between 2.8 p/kW and 5.4 p/kW. At the same time, the price of natural gas is rising rapidly from US$2 per million British thermal units (MBtu) in 2010 to a current domestic price close to US$8 per MBtu, with imported gas costing between US$9 and US$18 per MBtu. In contrast, local solar photovoltaic (PV) module prices have fallen by 75% since 2008, with a solar energy price of US$4.5 per MBtu [11].

In the UK there was a feed-in tariff for solar PV of around 12 p/kW (17 ct/kW) depending on the size of the system, but this has been dramatically reduced to around 1.63–3.69 p/kW(2–5 ct/kW) from 1st January 2016. There are concerns that this will mean that there will be no incentive to invest in this technology. Having said that, recent data from Germany shows that the cost of solar PV is coming down and was around 9 ct/kW in 2014 [53]. Furthermore in countries such as Brazil and Uruguay recent projects are showing costs of around 7 ct/kW.

[1] Rate of exchange: £1 = 5.55 dirham.

In addition to pricing considerations, the availability of solar energy also needs to be considered. The amount of incoming solar radiation to the UK is considerably less than the UEA due to its northern latitude and reduced solar irradiance due to cloudiness. This will always limit the maximum solar energy that can be utilised compared with a more southerly location such as Masdar City. In fact, the amount of solar irradiance for Birmingham is 4.7 kWh/m^2/day (June/July) [54] compared with a value for Masdar of 7.2 kWh/m^2/day (June) [54]. The demand for energy also tends to differ as temperatures in Abu Dhabi are much higher (around 48 °C in summer) with an associated demand for air conditioning (up to 60% of residential electrical load) [11]. In the UK, the demand for energy tends to be high when it is cold and cloudy, particularly in winter. In summer, the demand for air conditioning is not as high, though it is increasing [55].

3.4. Energy supply and demand: Masdar City and Birmingham

Masdar, the energy company, was created to establish a new sustainable energy industry in Abu Dhabi with the goal of using the city as a case study that can be employed at other locations. There have been challenges to the city project since its initiation, with modification of some of the original plans due to reduced funding caused by the world-wide economic disruption of 2008. Plans for pod-based rapid transport cars had to be modified to a more modest system, while not every building will now have rooftop solar panels, and electric battery-powered cars are allowed in the city when originally the city was to be car-free [26]. Electric buses currently serve the residential areas.

The current total energy consumption (operations and construction) for the whole of Masdar City is 5.43 ktoe (63,111 MWh) (2014). This is 0.3% of Birmingham's total of 1.66 Mtoe (19.3 TWh) in 2012 [50].

Masdar City is powered from a number of sources both internal to the city as well as from outside its boundaries. The SHAMS 1 [56], a stand-alone 2.5 km^2, 100 MW Concentrated Solar Power (CSP) plant, has been built approximately 100 km from Masdar with an estimated cost of US$600 million. This plant is one of the largest of its type in the world and displaces 175,000 t of CO_2 annually [25]. It generates electricity from the sun's heat rather than sunlight, as used by solar photovoltaic technology. In addition, Masdar City is supplied by another 0.2 km^2, 10 MW solar photovoltaic plant within the city, which provides 17,500 MWh/yr and is linked to and contributes to the national grid of Abu Dhabi Emirate) [85]. There is a 1 MW photovoltaic panel on the roof of the Masdar Institute of Science and Technology and the solar panels on Masdar headquarters generate 340,000 kW h per year [57].

Within Masdar, 75% of the total hot water is produced by solar energy, and fresh air handling units in the Siemens building have led to a 75% latent and sensible heat recovery. The Siemens Building, IRENA Building and the Incubator Building have angled facades to reduce solar glare and heat gain (30% reduction for the Incubator Building) [25]. Other initiatives include a solar cooling project, which is expected to work as a 170 kW chiller, and a geothermal cooling project, which has involved digging two 2.5 km deep wells [58]. A 45 m tower in Masdar City, based on traditional Arab technology, is also used as a cooler by directing hot air up and out of its surrounding area as well as bringing cooler air from aloft down to the surface. A 100 kW thermal power plant is being established that will convert solar energy into thermal energy through a set of reflective mirrors.

Power usage in Masdar City is monitored through the Building Management Systems (BMS) and shown through a series of video screens in the buildings demonstrating usage. Table 3 shows energy consumption for the main buildings in Masdar for two periods October 2013 to September 2014, and October 2014 to September 2015 [20]. There are a number of points to consider. Many of these buildings moved from the construction phase in 2013 to the operational stage in 2014. Due to this, the Siemens building and the Incubator building have seen a large influx of tenants. In addition, the buildings with the highest energy intensity belong to the Masdar Institute. This is attributable to the Institute being a research facility with energy-demanding activities. The SAF (Sustainable Administrative Facilities) building is regarded as a more typical office building and, together with Masdar Institute 1A and North Car Park, also has energy data for 2013 (which are slightly lower than 2014 and not shown here). Data are shown for 2014 for the more recent buildings (IRENA, Siemens HQ and the Incubator). IRENA has only recently been officially opened (January 2015) hence its low energy intensity value for 2014. A detailed case study analysis was carried out for the Siemens building for 2014. Some of the data are estimated as the reporting period runs from October 2013 to September 2014 but the study shows how the building's energy use is around 2824 MWh with an energy intensity of 117 kWh/m^2 [25]. This compares with a LEED (Leadership in Energy & Environmental Design) baseline figure of 4936 MWh (204 kWh/m^2 energy intensity) and an Abu Dhabi average of 8039 MW h (333 kW h/m^2 energy intensity). For the 2014 data, the greatest cooling use for the building was in August (150 MW h) [25]. The more recent data covering the period October 2014 to September 2015 shows how the energy intensity rose for the Masdar Institute 1A, the Siemens Building and the Incubator Building due to increased occupancy. Furthermore the Siemens building and the Incubator Building contain retail stores and catering outlets which contribute to their energy use. From these data and the percentage decreases in energy consumption from 2014 to 2015 noted in [20,p.53] (5% decrease in energy consumption for Masdar 1A and 31% decrease in energy consumption for Masdar 1B) it was possible to calculate the energy consumption for 2015, using the Gross Floor Areas (GFAs) for each of these buildings and the energy intensity data. The decrease in energy consumption between 2014 and 2015 for the Masdar Institute buildings (1 A and 1B) is due to enhancement of Energy Management in these buildings (optimisation of cooling and the use of set point temperatures). There are no light switches or water taps in the city. Movement sensors control lighting and water in order to cut electricity and water consumption by 51% and 55% respectively [59].

In contrast, Birmingham is highly dependent on fossil fuels for its energy as shown in Fig. 2. From the sub-national Department of Energy & Climate Change (DECC) data, the total energy consumption for Birmingham (2012) was 1.66 Mtoe (19.3 TWh). This is 1.3% of the total energy consumed by the UK (126 Mtoe). The distribution between the three energy sectors, as shown in Fig. 2 [50]. The domestic (38%, 626.3 ktoe) and industry sectors (37%, 607.3 ktoe) consume 75% of the city's energy, with the transport sector consuming around 25% (425.8 ktoe). Industrial consumption is the same as the UK percentage (37%, 47 Mtoe), while the domestic sector is higher than the UK national value of 33% (41 Mtoe) and the transport sector is lower (30%, 37 Mtoe). Given the historical background of car making, along with road construction, in the city this finding is somewhat unexpected; however as the housing sector is so large, domestic energy consumption is correspondingly greater. Household heating dominates the domestic consumption of gas [60], while private cars are the major user of petroleum fuel, including diesel [61].

It is not possible to distinguish between residential and commercial energy use within Masdar as the students are living within the Masdar Institute Building. There are 102 apartments within 1A and 221 in 1B [62]. In terms of transport, the city originally planned to use a battery-powered auto-piloted 'personal rapid transit' (PRT) system whereby passengers would be transported in pods beneath the city [63]. This system was scaled down and the city was not elevated as originally designed. The city currently

Table 3
Size, energy consumption and energy intensity for the main buildings in Masdar (2014). Source: [20,25].

Building name	Energy consumption (MWh) 2014	Occupancy[a] (%)	Gross floor area [25] (m^2)	Energy intensity (2014) (kWh/m^2)	Energy consumption (MWh) 2015[b]	Energy intensity (2015) (kWh/m^2)
IRENA HQ	537	100	32,064	16.75	2253	70.27
North Car Park (K13)	1138	–	–	See[c]	–	–
Sustainable Administrative Facilities (SAF)	3346	100	17,517	191.01	1734	98.99
Masdar Institute (1A)	9155	100	34,274[e]	299.60[c]	8697	309.29[f]
Masdar Institute (1B)	14,605	100	44,888[e]	325.97	10,077	224.5
Masdar Institute (1A & 1B)	23,760	100	79,162[d]	n/a	18,775	237.17[f]
Siemens HQ	1610	66	22,800	70.57	2498	109.56
Incubator Building	373	100	9709	98.87	1117	115.05
Total	30,764	–	161,252	–	26,377	–

[a] As of January 2015. Occupancy data are for 2014 for the Siemens Building.
[b] Calculated from total Gross Floor Area (GFA) and energy intensity 2015 (kWh/m^2).
[c] Includes the North Car Park.
[d] Both Masdar Institutes (1A and 1B). The total Gross Floor Area (GFA) for Masdar Institutes (1A & 1B) is 79,162 m^2 (p.99 [25]).
[e] Calculated from energy consumption 2015 (MWh) and energy intensity 2015 (kWh/m^2).
[f] Calculated from energy consumption 2015 (MWh) and total GFA for Masdar Institutes (1A & 1B).

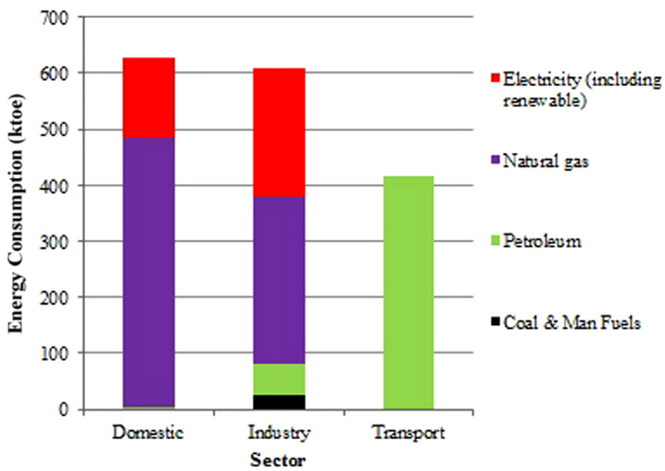

Fig. 2. Birmingham Energy Consumption (ktoe) in 2012 by sector and fuel [50]. Manufactured fuels include coal or petroleum consumed in Heat Generation, Energy Industry use, Industry, Public administration, Commercial and Agriculture.

uses 13 PRT carts (driverless pods), which run from the parking area at the city's outer edge to the Masdar Institute. There are also a number of electric vehicles developed by Mitsubishi. These run on a 16 kW h lithium-ion battery with a maximum speed of 130 km per hour and they can be charged from the rapid charging station at the SAF. The people who commute to the city do so by car, and then use one of the driverless pods to access the city.

For 2014, in terms of per capita energy use per citizen, for Masdar City's estimated total daytime population of 1618 student residents and workers (see Section 3.1 and Table 1) the city's energy consumption based solely on the main buildings in the city equates to 19.01 MWh per capita (compared with Birmingham's per capita value of 17.78 MWh (which includes transport energy consumption)). Accounting for the commuters (196,089 [64] coming into the city and 83,495 going out [64]), for the working-day population of Birmingham then the per capita value is 16.11 MWh per capita. If transport is removed and the city's energy consumption for commerce, industry and the domestic sector is used, this value falls to 13.22 MW h per capita. See Table 4 for calculations. In contrast, if other energy consumption for Masdar City is included (i.e. construction energy consumption and indirect energy consumption by chillers), this rises to 39 MW h per capita. This raises a number of issues such as the occupancy of some buildings (e.g. the Siemens HQ) where some energy may be used unnecessarily and the large energy use of chillers even though renewable energy is being used. With an increasing population the per capita value should decrease.

What emerges from the Masdar data is a system heavily dependent on electricity and solar energy, and thus there is a local "lock-in" to this energy source and the infrastructure of solar technology. In addition, its cars also rely on electricity. Given its size, and proximity to Abu Dhabi, Masdar City has the option of switching to use electricity produced from natural gas, which gives it some resilience should a problem arise with the panels or CSP plant. Furthermore, nuclear power will be added into Abu Dhabi's energy supply over the coming years as two new plants come online [44]. This highlights the importance of having a mixed energy supply.

Turning now to the UK case, we can consider how renewable energy contributes to the UK energy system. The contribution of all renewables to UK electricity generation is relatively low, just under 15% in 2013, although this is 3.6% higher than the previous year and has now reached 4617 ktoe electricity output (53.7 TW h) [65]. Capacity also grew by 27% (to 19.7 GW) between 2012 and 2013. The use of renewable energy is continuing to develop both in the domestic and industrial markets. There is increasing use of wind power with both offshore (21%) and onshore (32%) wind farms contributing a total of 53% of UK's renewable electricity [65], while the use of bioenergy is also increasing. However, it should be noted that in the cases of landfill gas, sewage sludge, municipal solid waste and other bioenergy sources a substantial proportion (around 70%) of the energy content of the input is lost in the process of conversion to electricity [66] – e.g. in 2013, 5834 ktoe of biomass (animal and plant), wastes (excluding wood and wood waste) and gases (landfill and sewage) combined produced only 1688 ktoe of electricity output [65]. The use of wood and wood waste (1067 ktoe) is more efficient with just over half being used by industry and the remainder by the domestic sector and other final users. Furthermore, a similar amount of biofuel (1091 ktoe) is consumed by the transport sector. A small amount of solar and geothermal heat (190 ktoe) together with heat pumps (91 ktoe) supply mostly the domestic sector and other final users [65].

Several local 'energy efficiency' initiatives have been adopted by Birmingham, including addressing heat loss from housing, making use of excess heat around the city and burning waste. For example, in 2012, the Tyseley Energy-from-Waste Plant, a large incineration plant, burnt 367 kt of household waste and produced 217 GW h of electricity [67], while a district heating scheme supplies energy (53 GW h) to several public buildings in the city centre including the new Library of Birmingham [68]. There are plans to extend the district heating network to include other private and public city centre buildings. Birmingham has very little solar renewable energy, limited to localised solar PVs on domestic housing and on some company roofs. Thus, in spite of Birmingham's ambitions, the contribution of renewable energy is currently small. Around 1710 GW h (2013) were generated from renewable energy sources with 125 GW h (7%) from solar panels

Table 4
Energy use per capita calculations (2014 data, Masdar; 2012 data, Birmingham).

City		Energy used by the city (MW h)	Population (people)	Per capita (MW h/person)	Transport energy consumption (MW h)	Energy used by the city without transport (MW h)
Masdar	Main Buildings	30,764	1618	19.01	n/a	n/a
	Other Direct Building Consumption[a]	10,882				
	Indirect City Consumption[b]	15,400				
	Construction	6065				
	Total	63,111	1618	39.01	n/a	n/a
Birmingham		19,302,852 [50]	1,085,400 [86]	17.78	4,952,603 [49]	14,350,249

Note that Birmingham's energy has been calculated by converting from mtoe to MW h using 1 Mtoe = 11.63 TW h and 1 TW h = 1,000,000 MW h.

[a] Other Direct Building Consumption is calculated from Direct Building Energy Consumption = 38,300 MW h [25] minus 27,418 MW h (Total for main Masdar Buildings (see Table 3) excluding SAF) [25] = 10,882 MW h.

[b] Indirect City Consumption includes energy used by chillers, a membrane bioreactor (MBR) which treats wastewater and the Beam Down project using concentrated solar power (CSP) (see [84] for further details). In 2014 these schemes used 15,400 MW h.

across the entire West Midlands Region [69]. However, this is an increase of nearly 70% from the previous year (including a rise of 42% in the use of solar panels), so it is currently a growing market. Exemplars of good practice include Birmingham Airport's installation of 200 solar panels on the roof of its terminal building generating 40 MW h and saving approximately 22 t of carbon dioxide each year [70] and Severn Trent Water, now producing methane gas from sewage to power homes (around 750 m^3 of gas per hour (5 ktoe per year)) [71] alongside their current use of wind turbines and solar panels.

The Birmingham Energy Savers scheme was launched in 2011 with the aim of upgrading up to 60,000 homes with more efficient heating systems and better insulation, backed by the Government's Green Deal policy. It was designed to cut household fuel bills, cut greenhouse gas emissions and support the region's growing green economy by creating thousands of jobs for suppliers. But in four years just 16 homes received the full Green Deal refit, and another 3000 installations were carried out using other funds and grants. Birmingham's cabinet member for sustainability, Lisa Trickett, said increased interest on loans for installation and cuts in subsidies meant residents using the Green Deal could end up paying more, rather than making the promised savings, on their energy bills after the work was done. The Green Deal interest rate was seven per cent, but many homeowners taking out loans for solar panels or a new boiler could access a personal loan at rates of three or four per cent. In the end the Council and its contractor, Carillion, had agreed an “amicable divorce” and wound up the Birmingham Energy Savers scheme [72]. However, it is estimated that during its operation the scheme saved 20,000 t of CO_2 [73].

4. Discussion

Both the UK and the UAE have a history of reliance on the oil economy, but with global trends of changes in climate and rising energy costs there is growing interest in low-carbon and renewable sources of energy. Birmingham and Masdar benefit differently from this increased interest and concomitant efforts to develop and implement renewable energy. Birmingham has the advantage of having established processes and infrastructures into which new technologies can be integrated with minimal disruption to the city's residents, workers and visitors, i.e. a known context in which interventions can be made and their effects determined. However, the converse effect of this existing set of infrastructure systems concerns the lock-in to current paradigms of energy supply and distribution – there is a component of inertia in these energy and infrastructure systems to overcome when seeking to make changes, thus compromising the ability to be flexible, and this inertia extends also to governance systems. In contrast, Masdar benefits from the lack of such processes and infrastructures, allowing for more radical interventions to be implemented. Both have aspirations towards resilience in is broadest sense [74], i.e. to effectively accommodate future change without serious disruption, and sustainability.

The ability of a country or a city to finance renewable energy technologies directly influences their development and implementation. With regard to Masdar and Birmingham, renewables are expensive when compared with the current (direct economic) cost of oil and natural gas (the primary sources of energy in the UK and UAE), and thus market-led economics tend to overlook them. In the UK, the renewable energy market is gaining strength, helped in part by policy and governance initiatives such as feed-in tariffs for solar PV panels and planning law exemptions for some wind farm developments. However, there are severe budgetary restraints both at the National and Local Government level, which limits the ambitions of many City Councils to advance this renewable energy agenda. In Masdar City, finance, essential for the concept initially to be realised, has been far less of a concern, being derived from oil revenues, although financial limitations emerged with the 2007/2008 economic downturn. Masdar has, however, demonstrated a vital need to be cost conscious since economic viability is a core component of sustainability. Energy has been cheap and subsidised by the Abu Dhabi Government, but steps are underway to link price with usage to make citizens more aware of their energy use. Unlocking finance to support renewable energy is crucial if a city is to reduce its carbon emissions, though for projects as ambitious as Masdar City's the costs are substantial and beyond the reach of most countries, let alone cities.

Birmingham can learn much from Masdar City's experiences with new technologies, particularly with regard to solar panel research and returns on investment. Although the UK climate is not as sunny as the UAE's, it is helpful to establish different panels' performance and energy efficiencies under temperatures ranging up to the high end of global extremes. The use of the wind tower in Masdar City for cooling at street-level is also of interest, particularly as the global climate warms and energy demand for air conditioning in the UK rises. Wind towers could possibly be used to combat the'heat island' effect in UK cities, alongside attention to building shading, street width and orientation, and the creation of wind tunnels, which are proving effective and should be considered for new developments through building layout strategies. These can be integrated into the green infrastructure strategies that Birmingham is adopting as part of its biophilic city status, which afford cooling as part of their ecosystem service provision – a further addition to city resilience by naturally lowering the energy demand. The converse lessons to Masdar are, of course, inhibited by its desert location, and serve to emphasise that sustainability is determined locally – local conditions set local priorities. It equally points to the interconnectedness of city utility service provision in a wider sense that for citizens' needs: for green infrastructure provision in Masdar there would be a considerable water requirement for irrigation, which in turn is highly energy intensive to provide.

Masdar City's buildings provide a helpful demonstration of improved building efficiency in terms of both water and power consumption. Other areas of particular relevance to Birmingham include Masdar City's work on smart grids, metres and appliances, as well as studies into an urban systems management platform across the whole city, green transportation, day lighting systems, and a sustainable supply chain. Masdar City's power grid operators have access to comprehensive data on how energy is being used at any given time from each property and can directly control high rates of consumption to balance supply with demand. Masdar has the benefit of installing smart grids prior to building occupancy and thus the consumer knows what to expect, whereas in existing cities, such as Birmingham, energy fittings need to be modified to convert to a smart grid while users' concerns around a change to their system need to be addressed.

Masdar is a young city and has much to learn from an established city such as Birmingham that has seen many transitions over centuries, amongst which are the pitfalls of an over-reliance on one industry and a lock-in to infrastructure systems that incur large costs to change – flexibility and means of adaptation should be designed into systems from the start. Governance systems should also reflect this desire to be flexible and adaptable, and avoid lock-in, but equally must reflect and be sensitive to drivers of change, which have the potential to change the context in which a set of proposed city interventions will be implemented [75]. Moreover Masdar City must reflect the aspirations of its citizens, as well as its city leaders and the businesses that drive its prosperity, suggesting that new forms of governance should be trialled and introduced as the city grows – a further compelling argument for experimentation. It is important that Masdar City develops a solid economic base and develops its focus on research and development to fund further growth. Moreover to achieve long-term success the city must be resilient in the face of changes in the global economy (e.g. decreasing revenue from the sale of oil and natural gas, on which it has relied) and an increasingly arid climate.

As Masdar City matures, its population will grow. It will move from 'creating something from nothing' to 'changing what already exists'. In other words, it will create a legacy of which it will have to take increasing cognisance as it further develops. It will become ever more important to consider the wellbeing of its citizens, e.g. ensure there are adequate environmentally-attractive open spaces and naturally vegetated areas for people to relax in and 'consume' the ecological ecosystem services they have to offer (citizens' connection to nature supporting wellbeing), as well as including them in decision making about the city's future development. Referring again to the city's context (a desert setting), this balance of green versus built environments for communal use will be different from that potentially available in Birmingham, which places potentially greater value on green spaces – this perspective is helpful when implementing designs for urban form, since sensitive engineering of urban spaces can bring about a healthy balance of social and environmental benefits from different 'gathering' spaces in cities.

Processes and infrastructures will increasingly benefit from integration to increase security of supply as well as efficiencies. For example, Birmingham's research into hydrogen fuel cells for cars could prove applicable in Masdar as existing desalination plants could be used to extract hydrogen. Other operational schemes used by Birmingham City Council, such as the reuse of waste, energy from waste and district heating (the same principles apply to district cooling), could also be relevant to Masdar, as well as methane gas extraction from sewage works and research on biofuels and cryogenic energy storage. New technologies, processes and the linkages between them must be carefully considered to prevent 'lock-in', i.e. their introduction should be designed with flexibility and adaptability in mind. This is a combination not only of the choices made (e.g. to prioritise solar power), but also of the sequencing of those choices (e.g. roof pitches must be set to maximise the effectiveness of roof-mounted solar panels, as must the orientation of building, otherwise the benefits of the panels will be reduced) [75]. This takes foresight and directed action, starting at the conceptual design phase, and should feature in the business case so that the investment opportunity is transparent. Yet equally the business case must embrace all of the potential benefits across the three pillars of sustainability (economic, social and environmental), and these potential benefits should be tested in the current context – taking each in turn, are the necessary conditions in place for that benefit to be delivered – and in the far future. The Designing Resilient Cities methodology is helpful in this [66].

However there is another aspect to the design of resilient cites that is embedded in 'future-proofing' design methods, such as [66]: the use of future scenarios. Crucially this provides a means of experimentation free from the concern that a City Council cannot be allowed to fail when making investments – a concern that is perhaps felt more keenly in Birmingham with its budget constraints and pressure on service delivery. There are several far future scenario techniques that can be employed (e.g. [76,77]) and all start by removing the users from the constraints of the current context – they ask 'what if? ' questions. Sitting alongside the future visioning process, there needs to be a methodology that establishes the current performance of a city, across all three pillars of sustainability, and then allows future performance to be established with an intervention in place [78]. By testing a series of potential interventions, and determining their likely efficacy in extreme-yet-plausible futures [66] and against aspirational futures [78] – i.e. a process of thought experiments – investments in innovative solutions to the problems facing cities can be made with far greater confidence of success.

5. Conclusion

Two very different cities have been compared. Masdar, in terms of size, is not currently a city, yet has aspirations to develop into one. Whether this succeeds or not is dependent upon its attractiveness for inward migration as a place to live, work and play and its ability to generate its own revenue for future growth. Moreover, as it develops the legacy, and 'lock-in', of today's decisions will echo the constraints and opportunities currently experienced by Birmingham. The development of Masdar has provided inspiration and ideas to neighbouring Gulf States, and raised on their political agenda the issues of renewable energy and sustainability by providing a demonstration of what is possible.

Both Masdar and Birmingham have aspirations to be low-carbon cities. Masdar has had a good start given its size and building restrictions, which only allow low-rise energy-efficient buildings, and the introduction of smart metering to provide comprehensive performance data. Data from such buildings can inform both operational practicalities, including behavioural changes, and where potential savings can be made, and these lessons can translate into more energy-efficient new and retrofitted UK buildings. Furthermore, with the aridity of the UAE climate, it is instructive to see how this climatic challenge is addressed since one potential future UK climate context (longer periods of drought) is now demanding serious consideration. Masdar can learn from the mistakes of Birmingham such as the infrastructure lock-in that accompanied a philosophy of development based on 'domination of the car' in the 1960–70s, and, though this lesson appears to have been accounted for in their focus on public transport and battery-powered vehicles, it must be recognised that whatever approach is adopted will have the potential to 'lock in' operations and behaviours around physical infrastructures – today's decisions are tomorrow's legacy. Masdar can also benefit from Birmingham's experiences of creating change in an existing 'locked-in, legacy' context, by designing to accommodate future change – adaptability, flexibility and nimbleness become the designers' watchwords.

Looking across all the lessons to be learnt by Birmingham and Masdar in relation to energy, five core issues emerge:

1. *Innovation and experimentation.* Innovation requires talented people and, often but not always, money (constrained funds can be a driver of innovation). Experimentation, however, traditionally requires talent and money. Masdar City benefits from attracting talented citizens, students and businesses and from access to generous national funding. This has allowed it to blossom as an international demonstrator and 'city lab', and thus attract more talent and more money [27]. Birmingham, suffering from the combined effects of budget cuts and the global financial crisis, has limited means to take risks and experiment with alternative energy paradigms, thus impeding its practical progress. Other drivers, such as a legal requirement to lower carbon emissions, therefore underpin radical change, with innovation providing the necessary enabler. Experimentation here is best achieved via future scenario modelling and thought experiments.
2. *Lock-in.* Energy supply and demand form a complex system, sitting in an even more complex system-of-systems when linked with other resources such as water and food, and all other city systems with which it must effectively synthesise.

Holistic understanding of these systems is essential if flexibility and adaptability is to be designed in and lock-in is to be avoided [75]. In particular, existing infrastructures and forced compliance with existing processes and procedures (e.g. via regulation) can lead to undesirable lock-in. Masdar City benefits from starting from a blank slate, whereas Birmingham must negotiate a plethora of existing processes, procedures and (an ageing) infrastructure. However, with this comes experience and understanding of the long-term risks. If Masdar City is unable to learn from what has gone before, it risks creating an unsustainable legacy for future generations, particularly given that infrastructure systems are both expensive to create and typically have long design lives.

3. *Balance.* The economic, societal and environmental aspects of sustainability are all critical. Unduly emphasising one can lead to negative consequences for the others. Despite Masdar City's sustainability focus, with the additional cultural aspect included in Estidama (Arabic for Sustainability) [8], there is evidence it is concentrating upon economic goals at the particular expense of social cohesion [27]. During the 20th Century Birmingham did the same, focussing on the car industry. It has since moved to a largely service industry and has recently obtained biophilic city status [33], and though many social issues remain unresolved [79,80], new methodologies provide a means of achieving this balance [76,78].
4. *Resilience.* Despite increasingly-sophisticated predictions of the future, none are reliable and shocks such as extreme weather due to climate change and political instability increasingly erode their efficacy. The use of future scenarios [66,76] should therefore be adopted to explore likely vulnerabilities of strategies and new developments. Masdar City and Birmingham may have different experiences of shocks and slower yet fundamental change, but to ensure their longevity both must make efforts to future-proof the decisions they take today so that they continue to deliver what was intended into the future [81].
5. *Governance.* It is encouraging that both cities have vision statements [8,32] that include aims to be as sustainable and resource secure as possible, and that they are both intent on providing demonstrations of how this might be achieved. To be successful, these aims must permeate all city policies and sit at the heart of the city's vision [82]. Masdar City has been created around these aims, but as it grows the aims risk becoming diluted amongst the melee of city life. In contrast, Birmingham has to incorporate these aims into its existing governance structures, policies and processes. To do this it must influence and harness a variety of drivers for change including the will of its politicians, citizens and businesses [83].

In the end the responsibilities lie with the cities of the world to learn from each other. This will lead to a greater understanding of what is required, and what can be appropriately applied – in terms of technology, investment, expected 'user behaviours', procedures, processes and governance – if it is to be sustainable. This will be particularly important as the global climate changes and cities need to ensure that they are resilient, robust and sustainable in the face of, perhaps radical, change if they are to survive. What this paper has demonstrated is that lessons from very different contexts can be extremely valuable, spanning the temporal dimensions of sustainability and resilience (e.g. Masdar City's consideration now of the problems of future 'lock-in', and Birmingham's reaction to radical climate change).

Authors' Contribution

SEL and PB conceived of the analysis. SEL led the analysis and assembled the data for the paper. PB, JML and CDFR contributed to the structure of the analysis and its interpretation in the context of future, liveable, sustainable and resilient cities. All authors co-wrote the paper.

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