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Environmental and natural resource implications of sustainable urban infrastructure systems

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Abstract

As cities grow, their environmental and natural resource footprints also tend to grow to keep up with the increasing demand on essential urban services such as passenger transportation, commercial space, and thermal comfort. The urban infrastructure systems, or socio-technical systems providing these services are the major conduits through which natural resources are consumed and environmental impacts are generated.

This paper aims to gauge the potential reductions in environmental and resources footprints through urban transformation, including the deployment of resource-efficient socio-technical systems and strategic densification. Using hybrid life cycle assessment approach combined with scenarios, we analyzed the greenhouse gas (GHG) emissions, water use, metal consumption and land use of selected socio-technical systems in 84 cities from the present to 2050. The socio-technical systems analyzed are: (1) bus rapid transit with electric buses, (2) green commercial buildings, and (3) district energy. We developed a baseline model for each city considering gross domestic product, population density, and climate conditions. Then, we overlaid three scenarios on top of the baseline model: (1) decarbonization of electricity, (2) aggressive deployment of resource-efficient socio-technical systems, and (3) strategic urban densification scenarios to each city and quantified their potentials in reducing the environmental and resource impacts of cities by 2050.

The results show that, under the baseline scenario, the environmental and natural resource footprints of all 84 cities combined would increase 58%–116% by 2050. The resource-efficient scenario along with strategic densification, however, has the potential to curve down GHG emissions to 17% below the 2010 level in 2050. Such transformation can also limit the increase in all resource footprints to less than 23% relative to 2010. This analysis suggests that resource-efficient urban infrastructure and decarbonization of electricity coupled with strategic densification have a potential to mitigate resources and environmental footprints of growing cities.

1. Introduction

As global urban population continues to grow, cities face the challenge of reducing the environmental and natural resource footprints while providing essential services to their populations. Addressing these challenges means drastically reducing the urban resource consumption through resource efficiency (Swilling *et al* 2013). Among others, the urban infrastructure or more broadly socio-technical systems that provide key services like passenger transportation, the provision of commercial space, and thermal comfort are the major conduits through which natural resources are consumed and environmental impacts are materialized.

While cities must develop individual strategies to develop economically and socially, the effectiveness of these strategies will also be influenced by regional and global changes. The Paris Agreement, one of such changes, aims to reduce global greenhouse gas (GHG) emissions to limit the global temperature increase to under 2 degrees Celsius (UNFCCC 2015). Meeting these goals requires a substantial shift in the ways electricity is generated and the ways energy is used to provide the key services on which civilization relies. This transition requires investments in renewable and low-carbon electricity infrastructure combined with the infrastructure that enables more efficient use of energy, including energy-efficient buildings, alternative fuel vehicles and public transportation systems. This technological transition is expected to bring about changes in environmental impacts as well as consumption of natural resources like metals, land and water (Hertwich *et al* 2014, Suh *et al* 2017). Furthermore, urban morphology and density significantly affect the choice and efficiency of socio-technical systems and, in turn, cities' environmental and resource footprints. Thus, it is crucial to understand the combined effect of city-level socio-technical strategies and strategic densification for resource efficiency and regional transitions to a low-carbon economy.

While it is obvious that aggressive deployment of more resource-efficient socio-technical systems, decarbonization of electricity, and changes in urban morphology through strategic densification, which, collectively, are referred to 'resource-efficient urban transformation' in this paper, would reduce cities' environmental and resource footprints, a systematic quantification of such potential at a global scale has been lacking. One of the challenges in measuring the potential of resource efficient urban transformation at a global level is the fact that every city is unique; demographic, socio-economic, and their trajectories, as well as the geo-climatic conditions are different city by city. These parameters are important in shaping the scale of demand on and the choice of cities' socio-technical systems, and therefore a simple extrapolation based on a few cities will not provide a sufficient basis for understanding the global potential of resource-efficient urban transformation.

A broad spectrum of literature has sought to understand how changes in technology, economic conditions and governance influence the metabolism of cities as they develop (Swilling *et al* 2013). Much of this literature focuses on estimating energy consumption, GHG emissions or domestic material consumption (DMC) based on trends and changes in indicators like gross domestic product (GDP), population, population density, human development index (HDI) and climate (Singh and Kennedy 2015, Kennedy *et al* 2014, 2009). Kennedy and colleagues examined how climate, urban form, population growth and economic activity have influenced the energy and material flows of 27 megacities around the world (Kennedy *et al* 2015). Others have used top down approaches like input-output analysis to examine the relationship among environmental impacts, household consumption, and urban density (Huppes *et al* 2006, Baiocchi *et al* 2010, Jones and Kammen 2011, Minx *et al* 2013, Jones and Kammen 2014). Others have sought to link bottom-up analyses like life cycle assessment (LCA) with more top-down approaches like DMC or urban metabolism (UM) (e.g. Goldstein *et al* 2013). Heinonen and colleagues have also used hybrid LCA to examine how urban structures, lifestyle, and density influence the greenhouse gas footprints of urban areas (Heinonen and Junnila 2011a, 2011b, Heinonen *et al* 2013a, 2013b). However, the data requirements and technological precision of LCA studies presents a difficulty for modeling the entirety of a city's metabolism on a technology-specific level, especially for a large set of cities in the long term.

This article builds on previous LCA studies of resource-efficient technologies and cities' metabolism by using long-term scenarios to 2050 for a selection of 84 cities. We narrowed the focus to three key socio-technical systems and analyzed how the technologies that provide those services and their market shares will change as cities develop and as electricity is decarbonized over time. We then quantify how the aggressive deployment of resource-efficient socio-technical systems, strategic urban densification and regional transitions toward low carbon electricity generation will influence the environmental impacts and resource consumption driven by cities from the present to 2050. To accomplish this we use an integrated hybrid LCA model (Suh *et al* 2017), and incorporates city-level scenarios for the demand for key urban services, changes in urban density, and global electricity generation scenarios consistent with the International Energy Agency's (IEA's) 2 degree scenario (IEA 2012).

The three socio-technical systems selected were: (1) passenger transportation, (2) commercial buildings and (3) residential heating and cooling. For each of these systems we quantify the effect of deploying resource-efficient technologies on reducing the life-cycle GHG emissions, energy use, water consumption and metal consumption for a set of 84 cities by 2050, specifically focusing on: (1) bus rapid transit (BRT) systems (including diesel and electric drive-trains), (2) energy-efficient green buildings, and (3) district energy systems (incorporating heating and cooling). We used cross-sectional data on these 84 cities around the globe to relate the demand for key urban services and the business-as-usual market shares of efficient technologies to income, population, population density, heating degree-days and cooling degree-days. Understanding these relationships allows us to customize and scale-up LCA models using cities' unique circumstances including population and GDP projections to estimate the aggregate resource and environmental impacts of providing key urban services under resource-efficient and baseline scenarios.

2. Resource-efficient technologies

2.1. Methods and data

BRT, combined with high ridership, fuel efficiency and electric or alternative fuel drive trains present an opportunity to reduce the GHG emissions and other environmental impacts of providing passenger transportation to growing urban populations. In addition to buses themselves, BRT systems can include dedicated running ways, attractive stations, distinctive easy-to-board vehicles, off-vehicle fare collection, use of information technologies and frequent all-day service (Levinson *et al* 2003). BRT systems can potentially be implemented with any fuel type or drive train (e.g. biodiesel, compressed natural gas, electric or fuel-cell). BRTs have shown a 25%–75% increase in passengers in comparison to standard bus systems (Levinson *et al* 2003).

The environmental benefits of BRT systems and public transit are clear from the LCA literature. Chester *et al* (2013) emphasized the importance of including infrastructure in LCAs of transportation, noting that infrastructure requirements could increase the estimated GHG emissions of public transport modes by 48%–100%. This article found that the environmental impacts of infrastructure were less significant for bus systems compared with light rail. Because of this, BRT systems generally have fast energy payback times (Eckelman 2013), meaning that environmental savings can be achieved more quickly if ridership is uncertain. Also, the future amount of renewables in the electricity grid has the potential to reduce carbon emissions because electric buses or other vehicles could recharge their batteries from grids powered by low carbon energy (Chester *et al* 2013). Our analysis builds on the results of Cooney *et al* (2013) and a recent benchmark by the National Renewable Energy Laboratory (Eudy *et al* 2016) estimate the future life-cycle impacts of electric BRT.

2.2. Green commercial buildings

Promoting energy efficiency in the buildings sector is a crucial element of climate change mitigation scenarios (IEA 2013). Green buildings incorporate many different efficiency measures to reduce energy consumption and emissions, including: increased thermal mass, insulation, efficient lighting, on-site renewable energy, and demand management systems. Several standards have been developed to benchmark ‘green’ buildings, including the US Green Building Council’s LEED certification, IgCC, and ASHRAE 189.1. While these certifications vary in terms of their emphasis on energy, water or indoor air quality, most definitions include some standard for energy and water efficiency. In an LCA of green building certifications, Suh *et al* (2014) constructed a parametric LCA model for a three storey commercial building and found that the environmental benefits achieved by energy savings during the use-phase of green buildings outweighed the impacts of additional insulation and other materials requirements for GHG emissions and most other impact categories. Our analysis builds on Suh *et al* (2014) using region-specific parameters.

2.3. District energy

District energy systems can provide heating and cooling services to concentrated urban populations efficiently by developing ‘synergies between the production and supply of heat, cooling, domestic hot water and electricity’ (UNEP 2015). To date, district energy systems have been commonly found in developed regions with high heating demands, for instance northern Europe, but new district energy systems focusing on cooling are being planned in warmer countries such as India (UNEP 2015). District energy systems can be powered by waste-to-energy, natural gas co-generation, biomass, heat pumps, absorption chillers, solar thermal and can use sea-water cooling (UNEP 2015).

District energy systems require substantial up-front investment in infrastructure, including power plants, pipes, pumps, and building systems (UNEP 2015, Oliver-Solà *et al* 2009). Despite these upfront requirements, the impacts of providing heat or cooling using district energy are dominated by the combustion of fuels (Eriksson *et al* 2007, Oliver-Solà *et al* 2009, Knutsson *et al* 2006). While there are few available life-cycle studies of district cooling systems, the infrastructure requirements are similar to district heating systems, meaning literature on the energy and materials requirements of district energy infrastructure (Oliver-Solà *et al* 2009) and the energy performance of district cooling systems (Fahlén *et al* 2012, Chow *et al* 2004) can be used to model their life-cycle environmental and resource impacts.

3. Methods and data

We combine city-level scenarios with an integrated hybrid LCA model (Suh 2004, Suh *et al* 2004) to assess the environmental and natural resource implications of efficient socio-technical systems by 2050. First, we compiled a baseline hybrid LCA model for each socio-technical system including urban transportation, office buildings, and space heating and cooling using natural gas boilers and air conditioners adapting existing literature and databases (Taptich *et al* 2015, Deru *et al* 2011, International Energy Agency 2013, ecoinvent database) (see table 2 for the list of references and data sources used). These processes are connected to the baseline electricity grid-mix of each region for 2010, 2030, and 2050 following IEA’s baseline scenario. Second, we compiled hybrid LCA models for resource efficient (RE) alternatives to these baseline socio-technical systems adapting existing literature and databases (Hertwich *et al* 2014, Suh *et al* 2017). Covered in the models includes battery electric bus

Table 1. Overview of model and methods used to translate process.

Process life cycle inventory	Socio-economic and climatic variables	Method	Demand for services
Transport: Passenger cars, diesel BRT and electric BRT	• GDP • Population density • Population	Regression analysis (84 cities)	Passenger kilometers per year (pkm)
	• GDP • Population density	Regression analysis (84 cities)	Baseline ratio of public to private passenger kilometers
Commercial buildings: Baseline and green building	• GDP	Regression analysis to find jobs per capita, and literature estimates of m^2 office space per employee	Commercial building floor space (m^2)
		Estimates from USGBC (2016) on present market share of green buildings	Present and future market share of green buildings
Heating and cooling: Natural gas boiler, air conditioning, district heating, and district cooling	• Heating degree-days • Cooling degree-days • Population	Used IEA regional estimates and projections of household size (m^2), persons per household, and heating and cooling degree-days to estimate energy demand	Demand for space heating and cooling energy (kWh)
		Used IEA regional estimates and projections of household size and persons per household to estimate	Demand for district energy infrastructure

Table 2. Data sources used to model the life-cycle of socio-technical urban systems.

Socio-technical system	Technology	References
Transport	Passenger cars (gasoline)	(Taptich *et al* 2015)
	Bus rapid transit (diesel)	(Taptich *et al* 2015)
	Bus rapid transit (battery electric)	(Cooney *et al* 2013, Eudy *et al* 2016, Hawkins *et al* 2013)
Commercial buildings	Green office building	(Suh *et al* 2014)
	Baseline office building	(Deru *et al* 2011)
Heating and cooling	District energy infrastructure	(Oliver-Solà *et al* 2009)
	District heating and cooling	(Ecoinvent 2010)
	Natural gas boilers	(Ecoinvent 2010)
	Air conditioning	(International Energy Agency 2013)

rapid transit (Cooney *et al* 2013, Eudy *et al* 2016, Hawkins *et al* 2013), green office buildings (Suh *et al* 2014), and district energy infrastructure (Oliver-Solà *et al* 2009, Ecoinvent 2010). These resource-efficient technologies are connected to regional electricity grid-mixes under the 2 degree Celsius scenario of IEA (Hertwich *et al* 2014, IEA 2012). Third, these models are scaled up and re-parameterized for each of the 84 cities using e.g. the heating degree days (HDD) and cooling degree days (CDD), the population (UN-DESA 2014, UN Population Division 2015), income per capita (OECD 2016), and population density (Seto *et al* 2014) and their projections. We developed scenarios to project the changes in demand for passenger transport, commercial buildings and residential heating and cooling from 2010–2030 and 2050. Regression analysis and estimates from literature were used to relate population, income, and density to the demand for the services that the selected socio-technical systems render, and to estimate the market shares of technologies. Fourth, we re-parameterized the models under strategic densification scenarios by reversing observed urban density trends. Finally we calculated the life-cycle GHG emissions, water consumption, land occupation and metal consumption associated with the provision of the services under (1) baseline (BL), (2) resource-efficient (RE), and (3) resource-efficient with strategic densification (RE+D). Table 1 summarizes the processes used to scale up process life cycle inventories to the level of demand for services by cities in our model. A more detailed description is provided from the next section.

3.1. Development of city-level scenarios

To estimate how the environmental and resource impacts of cities can be reduced through deployment of resource-efficient technologies and urban densification it was first necessary to develop plausible scenarios for the demand for key urban services. This section outlines how scenarios were constructed for a set of 84 cities around the world. These 84 cities were selected based on the availability of detailed transport data from the UITP Millennium Cities Database for Sustainable Transport (Kenworthy and Laube 2001).

3.1.1. Scenario definitions

This analysis is based on three scenarios: (1) baseline (BL), (2) resource-efficient (RE) and (3) resource-efficient with strategic densification (RE+D). The BL scenario assumes continued growth in urban population and income, decreasing urban density, and marginal technological changes in the production of electricity and materials. The RE scenario includes the same population, income and density projections as in BL, but assumes a higher penetration of resource-efficient technologies (i.e. BRT, district energy and green buildings) coupled with decarbonization of electricity supply consistent with 2 degree Celsius climate mitigation scenarios. The RE+D scenario, in addition to high penetration of resource-efficient technologies, considers increasing urban population density by 2% per year from 2010–2050, in reverse of the observed trends showing population becoming less dense at that same rate (Seto *et al* 2014).

Using cross-sectional data for these cities and estimates from literature, we project the demand for passenger transportation, residential heating and cooling, and commercial buildings under a BL scenario as a function of income, density and population. We also estimate the expected market share of efficient technologies under the BL scenario and two resource-efficient scenarios that include high penetration of efficient technologies and strategic urban densification.

For both the baseline and resource-efficient scenarios, our model specifies the sources of electricity generation in nine world regions, comparing BL trajectories to a 2 degree Celsius scenario, where electricity is increasingly provided by low carbon sources following the IEA Energy Technology Perspectives scenarios (IEA 2012).

3.1.2. Demand and market share trajectories

For socio-technical systems with available data, multiple regression analysis was used to estimate the how the demand for urban services and the market shares of technologies providing those services change with income, population and density. These relationships were then used to estimate future trajectories of demand for urban services for the 84 cities considered. Available data did not always allow for a statistically significant inference of the relationship between demand for services and a socio-economic variable. Thus, in many cases the best possible estimates from literature were used. Such relationships can be difficult to distinguish, and may be complicated by social, cultural or political differences across cities or regions. In their article, Bettencourt *et al* (2007) show 'power law' scaling relationships for the properties of cities as they grow in population. Given these relationships, we generally hypothesize a similar power law relationship among our socio-economic variables and the demand for services in cities.

Data from the UITP Millennium Cities Database for Sustainable Transport were used to draw relationships between the socio-economic variables of population and density and the demand for services: passenger kilometers (pkm) per capita, the ratio of public pkm to private pkm, and jobs (Kenworthy and Laube 2001). Climate data for all cities was acquired from www.degreedays.net in the form of heating degree-days (HDD) and cooling degree-days (CDD) (BizEE Degree Days 2016). The relationships between HDD, CDD and the demand for heating and cooling were estimated based on baseline building models described in Deru *et al* (2011).

Multiple regression results used for the projection of future demand are provided in the supplementary information (SI) available at stacks.iop.org/ERL/12/125009/mmedia, along with further details of the baseline scenarios, city-level scenarios and market shares of technologies.

3.2. Hybrid LCA of socio-technical systems

LCA quantifies the environmental impacts of a product or service from extraction of raw resources to manufacturing, to use and then end-of-life. Assessing the environmental and resource impacts of resource-efficient technologies deployed in cities from 2010–2050 requires detailed life-cycle information for each specific technology. However, for this information to be applied to cities across the globe, information is needed about the energy and material production systems in the global economy and how these systems will likely change under baseline and climate mitigation scenarios. For this purpose, we constructed a hybrid LCA model to assess the changing impacts of low-carbon electricity generation technologies and resource-efficient demand-side technologies over the coming decades (Hertwich *et al* 2014, Gibon *et al* 2015, Suh *et al* 2004).

This hybrid LCA model combines a regionalized version of the ecoinvent 2.2 database (Ecoinvent 2010) with the Exiobase multi-regional input-output database (Tukker *et al* 2013), thus accounting for regional differences in the production of materials and energy (Gibon *et al* 2015). The mix of the electricity generation technologies and their impacts under the baseline resource-efficient scenarios are based on the IEA's 6 degree and 2 degree Celsius scenarios respectively (IEA 2012). The 2 degree scenario reflects the goal of limiting climate change to under 2 degrees Celsius by 2050. This model differentiates nine regions: China, India, OECD Europe, OECD North America, OECD Pacific, Economies in Transition, Latin America, Developing Asia, and Africa and the Middle East, accounting for regional differences in the technology mixes used to generate electricity and produce materials. The model also accounts for changes in the energy efficiency, materials efficiency and environmental performance of key industrial sectors, namely pulp and paper, iron and steel, aluminum and copper as explained in detail by Gibon *et al* (2015). Data on the materials requirements and future environmental impacts of low-carbon electricity generation technologies is adapted from Gibon *et al* (2015) and Hertwich *et al* (2014, 2015). Finally, the ReCiPe life cycle impact assessment method is to characterize life-cycle GHG emissions, metal consumption, water consumption and land occupation (Goedkoop *et al* 2009).

The life-cycle inventories of each socio-technical system are modelled based on various data sources, summarized in. Further details of the sources of data and the computation of results under these scenarios are included in the SI.

4. Results

This section presents the results of the scenario analysis for all 84 cities, highlighting the distribution of those cities' environmental and resource impacts as they grow under the BL, RE, and RE+D scenarios.

Box and whisker plots summarize the results of each scenario in each year by presenting middle 50% of cities (represented by the two-toned box), the median (the line dividing the box) and the minimum and maximum cities (the whiskers). By comparing the boxes representing the resource-efficient scenarios in 2030 and 2050 to the baseline scenario in 2010, 2030 and 2050 it is possible to observe the overall change in potential resource and environmental impacts. Scatter plots show the variation in the relationships between GDP per capita and environmental and resource impacts per capita for all cities and emphasize the potential to decouple those impacts from economic growth.

4.1. Passenger transportation

As cities develop, increasing in income and becoming less dense, there is an observed trend towards more private vehicles, namely passenger cars. For transportation, the RE scenario assumes that the ratio of public to private transport can be increased by a factor of 12 by 2050, which would increase the median percentage of transport provided by BRT in the 84 cities from 4% under baseline to 37% under the RE scenario. Under this RE scenario, total demand for passenger transportation follows baseline projections, with demand increasing as urban GDP increases and population density decreases. Because the RE+D scenario also considers a reversal of the baseline trend of declining urban density, our scenarios assume a decline in passenger transportation demand with more of that demand being met by public transport. BRT also becomes increasingly electrified by 2050 under both scenarios, reaching 90% of all buses by 2050. Furthermore, renewable and low-carbon energy sources provide a greater portion of electricity by 2030 and 2050, as discussed in the methods (section 3).

Figure 1 presents the resource impacts of meeting transportation demand projections in all 84 cities under each scenario. Although our scenarios assume that the total demand for passenger transportation grows as GDP and population increase, aggressive deployment of BRT could reduce GHG emissions and water consumption compared to 2010 while metal consumption and land increase at a slow rate compared to BL. Results suggest that high penetration of BRT coupled with low-carbon electricity and increased urban density can help decouple resource impacts from urban economic growth while providing greater amounts of transportation services. For all cities combined, figure 2 shows the percent reductions possible under each scenario.

4.2. Green buildings

The prevalence of green buildings is already high in many countries. In the United States, for example, around 40%–48% of new non-residential buildings incorporated a green building certification as of 2015 (USGBC 2016). Thus, the portion of green-certified buildings is likely to increase under the BL, so we assume 45% green buildings by 2050. The RE scenario assumes 100% green building penetration by 2050. While many factors influence the energy consumption of buildings in urban environments, this analysis uses a typical low-rise commercial office building to show how green building certifications and low-carbon electricity can be used to reduce the resource and environmental footprints of commercial space in cities.

Compared to the BL scenario in 2050, high penetration of green buildings under the resource-efficient scenario has the potential to substantially reduce impacts in all impact categories considered (figure 3). Summing the results across all 84 cities together, the resource-efficient scenario provides: (1) 53% reduction in GHGs, (2) 39% reduction in water consumption, (3) 27% reduction in metal consumption, and (4) 63% reduction in land use.

Although commercial building space grows under our scenarios as GDP and population increase, results suggest that high penetration of green buildings combined with low-carbon electricity supply can reduce GHG emissions by 2050 compared to 2010. Compared to BL, metal consumption, water consumption and land use grow more slowly by 2050. These results suggest that deployment of energy and water-efficient green buildings that incorporate on-site, renewable energy and consume low-carbon electricity can be an effective strategy at decoupling environmental and resource impacts from growth.

4.3. District energy

For this analysis, we assume that district heating and cooling systems require the same infrastructure requirements, except for the absorption chiller used to convert waste heat into chilled water. While district energy systems can utilize heat from several fuel-types and sources, district energy systems in this analysis

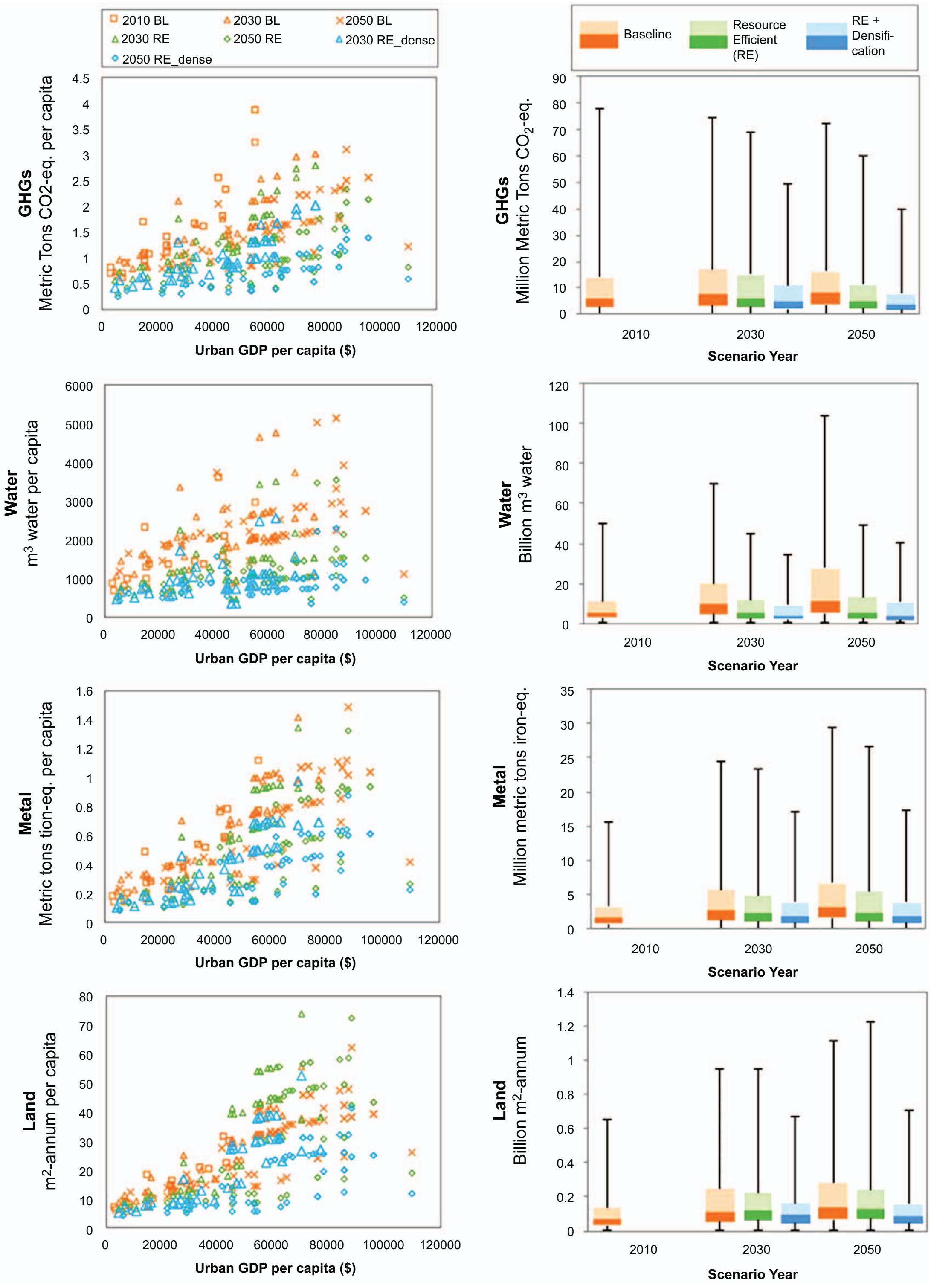

Figure 1. Impacts of BL, RE, and RE+D scenarios for passenger transportation in 84 cities. Boxes represent the interquartile range of impacts the border between the light and dark shaded area is the median. Whiskers show the maximum and minimum values among all cities.

use by-product heat from natural gas cogeneration. We assume distribution losses of 10% for both district heating and cooling (UNEP 2015), and that absorption chillers have a coefficient of performance (COP) of 0.6 (Ecoinvent 2010). In actuality, losses and efficiency vary seasonally, and further energy efficiency can be gained by utilizing seawater cooling in coastal cities (Chow *et al* 2004).

While the overall demand for heating and cooling grows, figure 4 shows that high penetration of district energy under the RE scenario can substantially reduce GHG emissions and land use compared to 2010, but could lead to greater metal and water consumption than under the BL in 2050 due to infrastructure requirements and direct water use. Summing all 84 cities together, the resource-efficient scenario provides: (1) 38%

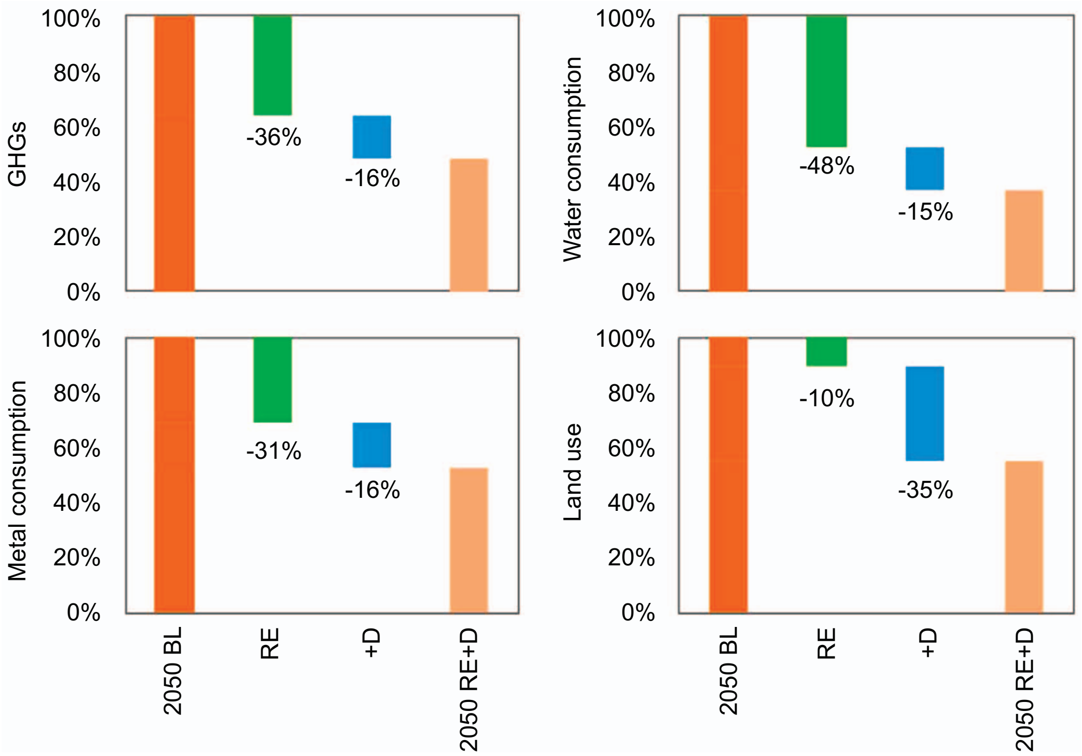

Figure 2. Potential impact of BRT on the environmental and natural resource impacts of transportation for 84 cities combined. Baseline (BL); resource efficient (RE); plus densification (+D).

reduction in GHGs, (2) 39% increase in water consumption, (3) 44% increase in metal consumption, and (4) 68% reduction in land use.

4.4. Combined effects of efficient socio-technical systems

Combining the aggregate results all three socio-technical systems can provide insights into the potential for resource-efficient technological transitions, increased urban density and decarbonization of electricity to reduce the life-cycle resource consumption and environmental impacts of cities by 2050.

Figure 5 shows the distribution of percentage reductions in environmental and resource impacts for all three socio-technical systems in all 84 cities. The vertical axis represents the number of cities with a given impact reduction as shown on the horizontal axis. For the standard resource-efficient scenario, most cities can see a 5%–20% decrease in land use, a 5%–30% improvement in metal consumption, a 40%–55% improvement in water consumption and a 40%–50% reduction in GHG emissions. When strategic densification is added, these improvements can be even greater. For the strategic densification scenario, most cities show 30%–40% improvements in land use, 30%–50% improvements in metal, 50%–65% improvements in water consumption and 40%–60% improvements in GHGs. These further improvements under the strategic densification scenario are due to the decreased demand for vehicle transportation that materializes when cities become denser.

5. Discussion and conclusions

We analyzed the potential reduction in environmental and natural resource impacts that can be achieved by resource-efficient socio-technical systems, low-carbon electricity supply and urban densification by 2050. We analyzed a sample set of 84 cities and used empirical estimates and relevant literature to project the demand for passenger transportation, commercial buildings, and heating and cooling from the present to the year 2050. These results were aggregated across the 84 cities to examine how such socio-technical transitions can contribute to reducing the environmental and natural resource impacts of future urban development. When all cities are combined, the results showed that 27%–53% reductions in resources impacts by the technologies considered can be achieved by 2050 through high penetration of efficient technologies. When a strategic densification scenario is overlaid on the resource efficiency scenario, the results showed 4%–14% additional reductions in environmental and resource impacts. In sum, the combination of resource-efficient systems and densification can achieve 46%–66% reductions compared to BL in 2050.

The sample cities analyzed represent a combined population of 515 million people, which would grow to around 753 million by 2050 under our scenarios. This total is sizeable and covers a wide cross section of the world's existing cities, however the sample population includes a greater number of cities in North

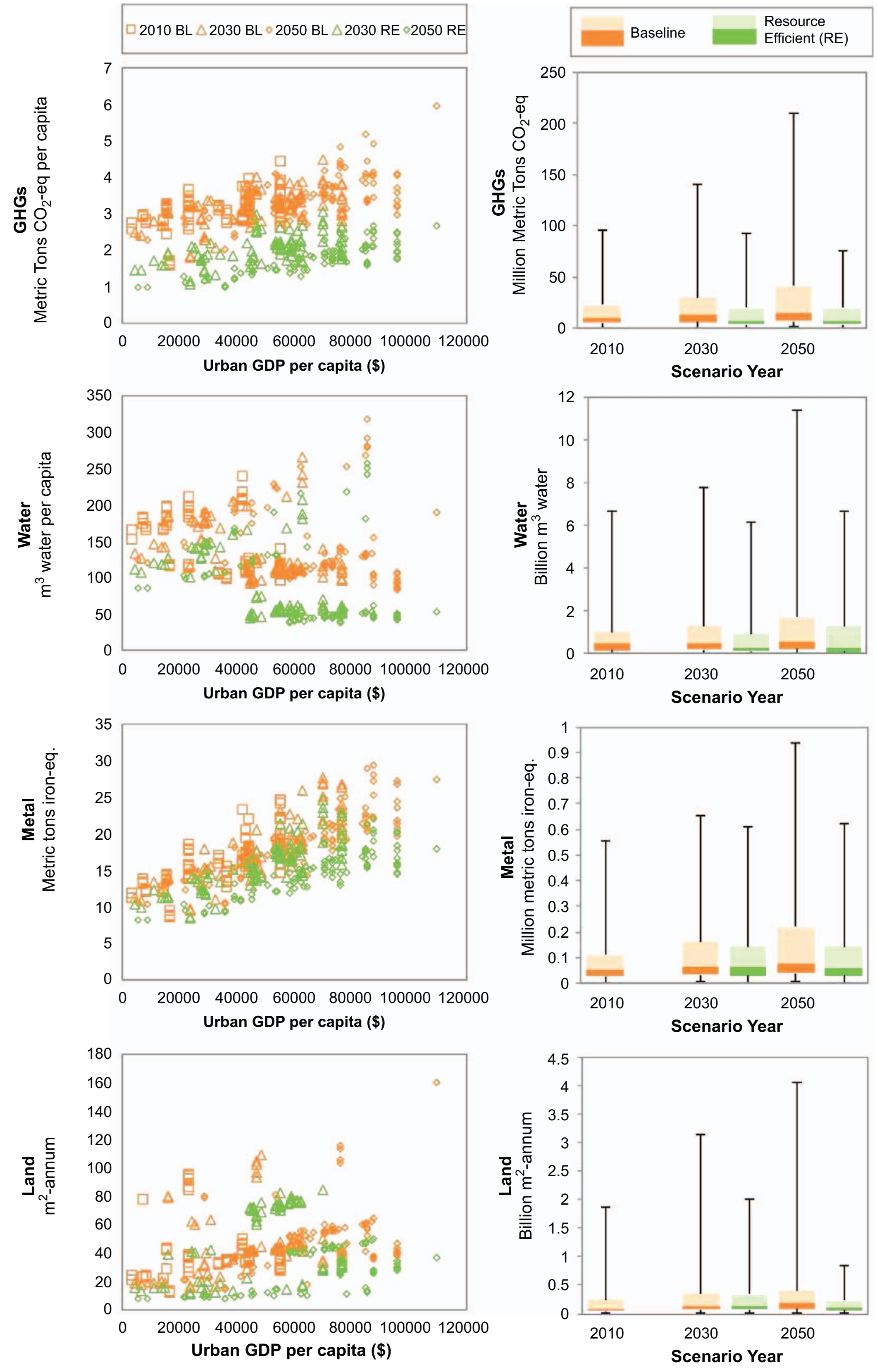

Figure 3. Impacts of BL and RE scenarios for green commercial buildings in 84 cities. Boxes represent the interquartile range of impacts the border between the light and dark shaded area is the median. Whiskers show the maximum and minimum values among all cities.

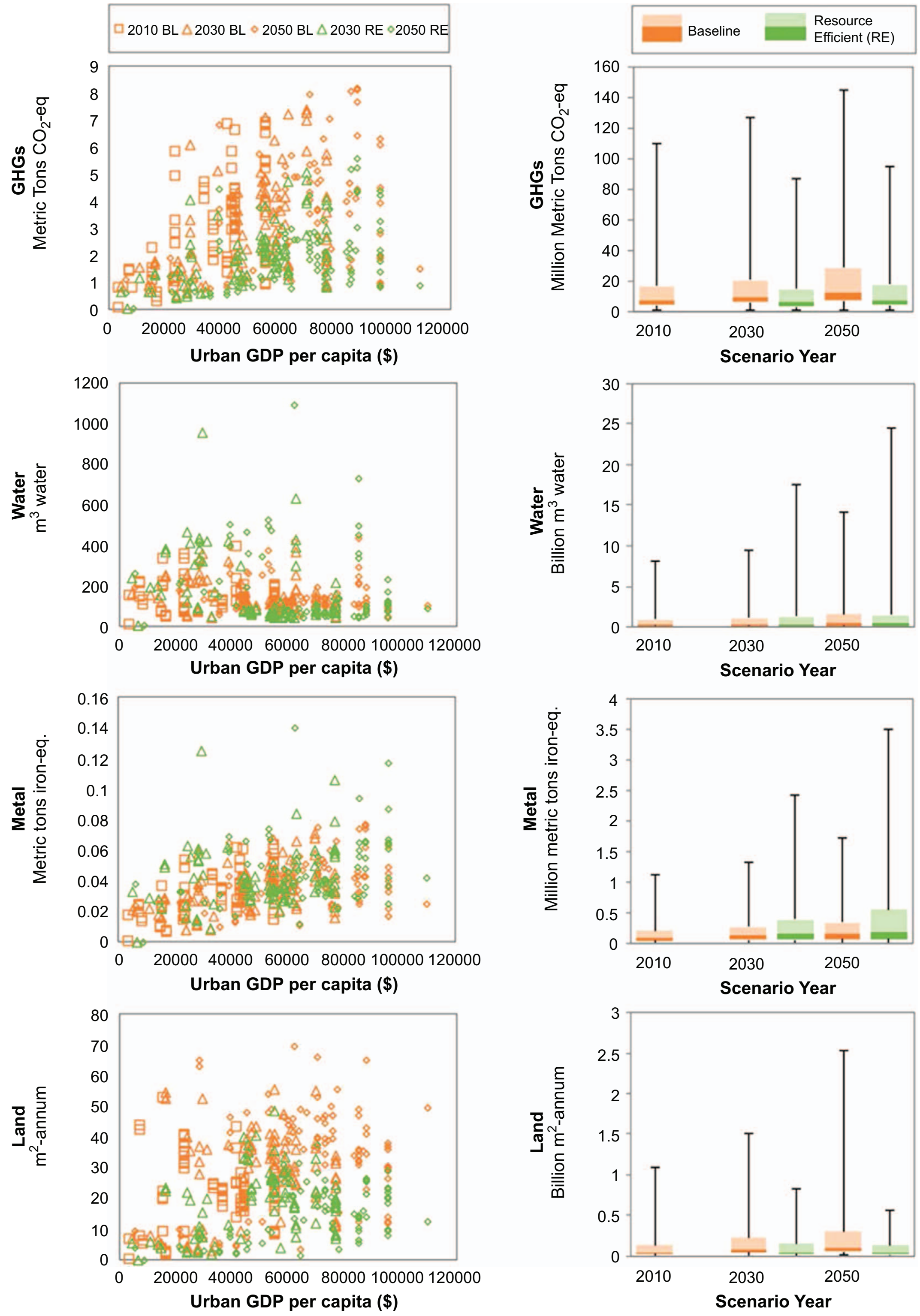

Figure 4. Impacts of baseline and resource-efficient scenarios for district energy in 84 cities. Boxes represent the interquartile range of impacts the border between the light and dark shaded area is the median. Whiskers show the maximum and minimum values among all cities.

America, Europe and Asia than other regions due to data availability. Further, many of the socio-economic geo-climatic variables used to project the demand for services have differing effects for different cultures and regions, meaning that these scenarios may not hold for every city. In this analysis the potential future trajectories of cities were simplified to gauge the impact of deploying resource-efficient socio-technical systems across the globe, but generally were designed to follow the observed trends according to Bettencourt *et al* (2007). Further, the level of analysis required for this assessment was only feasible for a few key technologies. It would be beneficial to look at both residential and commercial buildings, and to expand the scope

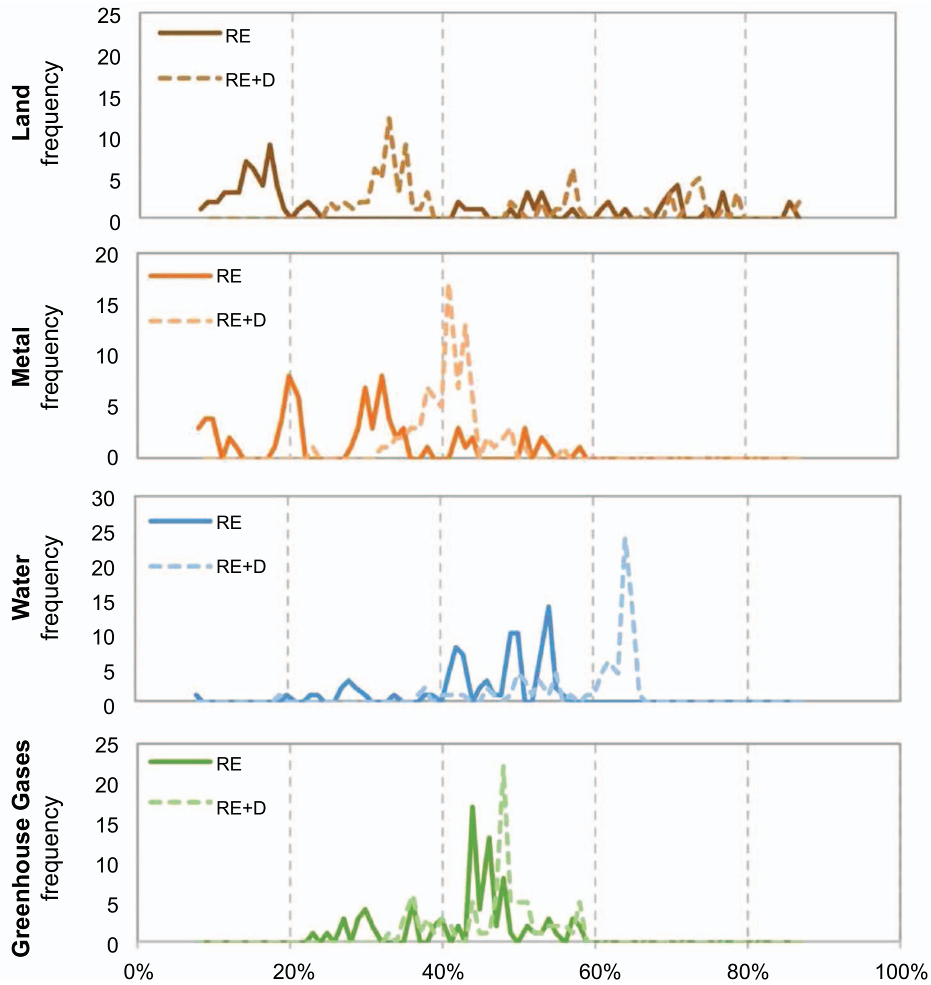

Figure 5. Frequency distribution showing the relative reduction in life-cycle annual resource and environmental impacts under the RE and RE+D scenarios for 84 cities in 2050 compared to the baseline scenario in 2050.

to other efficient transport options, including electric passenger cars and light rail. While the technologies analyzed are examples of some of the important technologies that can be used to reduce the environmental and resource impacts of cities, these technologies are limited to the buildings and transportation sectors. Including technologies related to producing and processing food, for instance, would likely also show large contributions to the water, land and GHG footprints of cities.

The results of this article emphasize the importance of transforming cities' socio-technical systems through resource-efficient technologies, increased urban density and low-carbon electricity supply. This analysis suggests that all together, these strategies could effectively decouple resource and environmental footprints from the future growth of cities around the globe. Under the baseline scenario, the environmental and natural resource footprints of all 84 cities combined would increase 58%–116% by 2050. However, under the resource-efficient and strategic densification scenarios, we observe that GHG emissions can be decoupled absolutely from the economic and demographic growth for the sample of cities considered, with GHG emissions reducing 17% by 2050 compared to 2010 emissions. At the same time, the resource footprints of metal consumption, water use and land occupation show a relative decoupling by 2050, growing by no more than 23% compared to 2010. In sum, this analysis supports the conclusion that city-level resource efficiency can be achieved by leveraging (1) aggressive deployment of resource-efficient technologies, (2) strategic urban densification, and (3) regional or global decarbonization of electricity.

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