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ORIGINAL PAPER

The effectiveness of Light Rail transit in achieving regional CO_2 emissions targets is linked to building energy use: insights from system dynamics modeling

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Abstract Cities worldwide face the challenges of accommodating a growing population, while reducing emissions to meet climate mitigation targets. Public transit investments are often proposed as a way to curb emissions while maintaining healthy urban economies. However, cities face a system-level challenge in that transportation systems have cascading effects on land use and economic development. Understanding how an improved public transit system could affect urban growth and emissions requires a system-level view of a city, to anticipate side effects that could run counter to policy goals. To address this knowledge gap, we conducted a case study on the rapidly growing Research Triangle, North Carolina (USA) region, which has proposed to build a Light Railway by 2026 along a heavily used transportation corridor between the cities of Durham and Chapel Hill. At the same time, Durham County has set a goal of lowering greenhouse gas emissions by 30% from a 2005 baseline by 2030. In collaboration with local stakeholders, we developed a system dynamics model to simulate how Light Rail transit and concurrent policies could help or hinder these sustainable growth goals. The Durham–Orange Light Rail Project (D–O LRP) model simulates urban–regional dynamics between 2000 and 2040, including feedbacks from energy spending on economic growth and from land scarcity on development. Counter to expectations, model scenarios that included Light Rail had as much as 5% higher regional energy use and CO_2 emissions than business-as-usual (BAU) by 2040 despite many residents choosing to use public transit instead of private vehicles. This was largely due to an assumption that Light Rail increases demand for commercial development in the station areas, creating new jobs and attracting new residents. If regional solar capacity grew to 640 MW, this would offset the emissions growth, mostly from new buildings, that is indirectly due to Light Rail. National trends in building and automobile energy efficiency, as well as federal emissions regulation under the Clean Power Plan, would also allow significant progress toward the 2030 Durham emissions reduction goal. By simulating the magnitude of technology and policy effects, the D–O LRP model can enable policy makers to make strategic choices about regional growth.

Keywords System dynamics · Regional model · CO_2 emissions · Energy use · Public transit · Urban sustainability

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Introduction

More than half the world population is now urban, and sustainable development challenges will increasingly be found in cities (UN 2015). Curbing energy use and CO_2 emissions while accommodating a growing population is a common urban challenge, and even a paradox (Rees and Wackernagel 1996). A widely promoted strategy to meet this challenge is

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compact, public transit-oriented urban development (Rickwood et al. 2008). The strategy holds that more compact cities reduce private vehicle use and encourage public transportation use, which is more energy efficient than private vehicle use (Newman and Kenworthy 1989; Ewing et al. 2008). However, for a clearer picture of how transit-oriented development impacts urban energy use, buildings must also be considered. In cities, buildings may consume twice as much energy as transportation (Steemers 2003), but the effects of increased density on building energy use are not as well understood (Rickwood et al. 2008; Larivière and Lafrance 1999) or not emphasized in transportation research (Gallivan et al. 2015; Transportation Research Board 2009) which often focuses on reducing VMT (vehicle miles traveled). We developed an urban system model to clarify how transit and compact development interact to affect urban energy use, and to identify potential side effects that enhance or detract from system-wide emissions reduction.

As a case study, we modeled the rapidly growing Research Triangle region of North Carolina (USA), which is planning to build Light Rail by 2026. The population in the Research Triangle is expected to double from the 2005 level by 2035 (Triangle Regional Transit Program 2012). To improve mobility, prevent sprawl, and concentrate growth along a transportation corridor, Durham and Orange counties are planning for Light Rail transit. At the same time, Durham County has set a goal of reducing carbon emissions 30% from a 2005 baseline by 2030 (ICLEI 2007). Progress toward these multiple regional goals can be projected with a computer model that forecasts the population, technology, and economic trends behind energy usage. In this paper we present the Durham–Orange Light Rail Project (D–O LRP) System Dynamics (SD) model to simulate how and to what extent the LRT and concurrent policies may affect regional energy usage and CO_2 emissions. The model was built in collaboration with stakeholders, including local sustainability, transportation, and urban planning officials.

Research questions and approach

Using the model, we address four main questions: (1) To what extent does the densification associated with Light Rail affect regional energy consumption and CO_2 emissions? (2) To what extent does Light Rail affect energy consumption and emissions by offsetting vehicle miles traveled (VMT) by car? (3) What is the relative magnitude of regional influences (Light Rail, transit-oriented development, solar capacity increase) versus outside influences (gasoline price, national trends in building, and vehicle energy efficiency) on regional energy outcomes? (4) Which regional strategies most effectively reduce energy consumption and CO_2 emissions?

The D–O LRP SD model simulates features of the regional energy and economic systems between 2000 and 2040, with and without Light Rail. By presenting results as a time series, the model expands on existing regional studies such as the Durham Greenhouse Gas Plan (ICLEI 2007), the Imagine 2040 regional plan (TJCOG 2013), and the Environmental Impact Statement for the Light Rail line (GoTriangle 2016) which present one baseline year (2005 or 2010) and one future year (2030 or 2040). Time series projections allow model users to examine both the magnitude and shape of trends. In addition, the use of a system dynamics model with a few seconds runtime enables many scenarios to be explored, compared to land use transportation models that require hours to run.

Literature context

Previous studies suggest that Light Rail transit can improve urban energy use efficiency, but with limitations. A global study on urban transportation energy use (Kenworthy 2008) found that in all regions, Light Rail used less energy per passenger-mile than automobile and was more energy efficient than bus, except in Eastern European cities. Nahlik et al. (2014) found that, over a 60-year period, transit-oriented development in Phoenix, AZ, could reduce total energy consumption and GHG emissions 40% compared to business-as-usual. Chester et al. (2013) found that the Los Angeles Gold Light Rail system could achieve life-cycle energy and GHG reductions, but only if at least 25% of riders had shifted from automobiles. Although much of the literature supports Light Rail as an energy efficiency strategy, there are known detractors; O'Toole (2008) suggests that energy-efficient automobiles may be more effective than Light Rail at reducing energy usage and CO_2 emissions, due to the large amount of energy required to build rail lines. In addition, the studies we cite on Light Rail energy use have, with the exception of Nahlik et al., not included effects of Light Rail on building development; we hypothesize that this is a key factor in how Light Rail affects regional energy use.

Because vehicles and buildings are major energy consumers, urban energy and emissions trends reflect transportation and land use patterns (Rickwood et al. 2008). We modeled these patterns using system dynamics, due to its ability to describe system interactions and feedback. System dynamics models represent a system as a network of stocks, flows, and information exchanges (Sterman 2000). In an urban system, stocks may include population, road length, and investment (Forrester 1969). Associated flows include immigration/emigration, new road construction, and tax revenue. Information exchanges include indicators such as congestion (calculated in real time as peak traffic travel time/free flow travel time). SD theory originated in business management (Sterman 2000), but has been applied to diverse systems including cities (Duran-Encalada and Paucar-Caceres 2009), water resources (Fiksel et al. 2013, Van Rooijen 2009), and climate (Sterman et al. 2012).

System dynamics models have often been used to forecast energy use and emissions in Asian cities, where rapid growth presents challenges for energy policy. Han and Hayashi (2008) used system dynamics to simulate CO_2 emissions from inter-city transport in China. They found that policies encouraging railway development, slowing highway growth, and imposing fuel taxes would result in the most CO_2 reductions, about 30% compared to business-as-usual by 2020. Their analysis was focused on transportation and did not include building energy use. Fong et al. (2009) considered both transportation and building energy use, modeling CO_2 emissions within an urban region of Malaysia, and found that a policy combination including vehicle and manufacturing energy efficiency, renewable energy, reduced rural–urban migration, investment in public transportation, and an economic shift toward service industries could reduce emissions 60% from a 2025 business-as-usual (BAU) scenario. A similar model in the USA is the IBM System Dynamics for Smarter Cities model (Hennessy et al. 2011), which integrates many urban sectors including economy, housing, education, public safety, health, transportation, emissions, and utilities. The model is applied to Portland, Oregon, for a 25-year planning horizon, but energy and emissions scenarios have not, to our knowledge, been published. Given these examples from literature, our model contributes to the field by (1) analyzing energy and emissions scenarios in an eastern US city; (2) considering both transportation and building energy use, linked by economic growth; and (3) anchoring on an ongoing transit project as way to explore regional scenarios.

Based on this literature background, we hypothesized that rail and associated densification would reduce VMT as well as regional energy consumption and CO_2 emissions. We hypothesized that these factors would be more affected by outside influences (energy efficiency trends, gasoline prices) than regional influences (Light Rail, compact development, solar panel installation). Also we hypothesized that a combination of Light Rail, dense redevelopment, renewable energy, and higher fuel costs might most effectively reduce regional emissions.

Methods

Study system

We divided the modeled system into two geographic boundaries. The outer boundary, which we named Tier 2, is

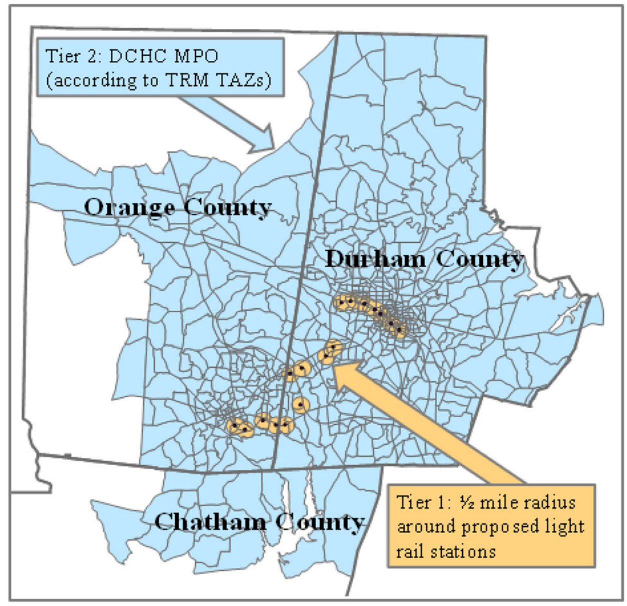

Fig. 1 Map of the D–O LRP SD model geographic tiers. *Note*: TRM TAZs refer to traffic analysis zones of the triangle regional model, the transportation model used by local planners

the Durham–Chapel Hill–Carrboro Metropolitan Planning Organization (DCHC MPO) area. The DCHC MPO is a Metropolitan Planning Organization (MPO) for transportation planning (Fig. 1). It covers an approximately 560 square mile area that includes the city of Durham and the towns of Chapel Hill, Carrboro, and Hillsborough. As of 2010, the DCHC MPO population was 403,000 (Organization 2012). In addition, the D–O LRP calculates outputs for a boundary within Tier 2: the combined area of half-mile radius zones surrounding each of the proposed Light Rail stations, referred to as Tier 1. A half-mile radius was chosen because urban planners usually consider it the maximum walking distance to a public transit station. Although Tier 1 is essentially a parallel model to Tier 2—containing similar features but functioning independently—under all scenarios except Business-as-Usual, changes in Tier 1 cause changes in Tier 2 variables, since Tier 2 contains Tier 1.

The Light Rail proposal has generated active local debate, which represents issues that other communities would face if they pursued transit-oriented development. Projected to cost \$1.47–1.62B (2015 dollars) to build (GoTriangle 2015), it is a large infrastructure project requiring federal (50%), state (25%), and local (25%) funding (DCHC MPO, Triangle Transit Board of Trustees, and Durham Board of County Commissioners 2011). Proponents argue that the 17-mile rail line between Durham and Chapel Hill, NC, would concentrate development near the Light Rail stations, reducing sprawl. High-density mixed-use development within the proposed transit corridor has been adopted by local governments as a growth management strategy (Triangle Regional Transit Program 2012). In contrast, rail opponents argue that the rail ridership projections (20,000–25,000 riders in 2040) are higher than what the area's population density would support, and note that local residences would be disrupted by construction and use of the rail operations and maintenance facility (GoTriangle 2015, 2016; Grubb 2015).

Stakeholder involvement

In the first phase of our modeling effort, a conceptual model for the D–O LRP model was designed with a high degree of input from stakeholders, including representatives from the regional transit authority, county sustainability and health departments, as well as city and regional land use and transportation planning departments. This form of stakeholder-driven modeling has been practiced for traffic congestion and air quality issues in Las Vegas (Stave 2002) and regional water planning challenges along the Rio Grande (Tidwell et al. 2004), and for water and economic planning in Maui, HI (Bassi et al. 2009). Involving stakeholders allows discussion of their mental models and can improve trust in the resulting computer model. The D–O LRP conceptual model served as a framework for the operational SD model, which evaluates a number of policy scenarios, many of which were suggested by stakeholders.

D–O LRP model construction

Using Vensim software (Ventana Systems, Harvard, MA) we built a system dynamics model simulating regional and urban growth in the DCHC MPO area. Variables in the model are simulated between 2000 and 2040, with a time step of 1/16 year (22.8 days), allowing a scenario to be run within a few seconds. During model building, we iterated between creating causal loop diagrams (CLDs) and using them to code the model. A CLD depicts material stocks and flows, information transfer between variables, as well as feedback loops.[1] The CLD is then coded into a system dynamics mathematical model using Vensim software. Besides simulation, Vensim allows sensitivity tests to determine how system output differs across a range of parameter values, such as the degree to which Light Rail stimulates demand for commercial building. The model was subjected to rigorous quality assurance tests, including parameter and structural sensitivity tests (US EPA 2016).

[1] Reinforcing and balancing loops amplify and limit change in the system, respectively. For example, VMT increases road congestion, which decreases VMT in a balancing feedback loop.

Causal loop diagrams (CLDs)—full model and energy sector

The model consists of seven integrated sectors, detailed in US EPA (2016). The core sectors are land use, economy, energy, and transportation; outcome-oriented sectors are water, health, and equity. This paper focuses on the core sectors, which are more directly connected to energy use. There are linkages both within and between sectors, to allow consistency across variables and feedbacks between sectors.

Figure 2 presents a CLD for the energy sector of the model, which includes variables from the other three core sectors. Some variable names have been simplified for clarity, and the coded model contains many more variables. Total energy use in the model is directly affected by: (1) changes in the energy efficiency of buildings and vehicles, (2) changes in residential and nonresidential building stock and vehicle miles traveled (VMT), (3) changes in the use of public transportation, and (4) changes in the proportion of residential building types [e.g., single family (SF) vs multifamily dwelling units] and commercial density through redevelopment. These changes in energy use by buildings and vehicles, along with any growth in renewable energy (solar or landfill gas), also affect modeled CO_2 emissions.

The connections forming the key feedback loops through the energy sector are shown in Fig. 2. Energy spending represents either a balancing or reinforcing loop on building and vehicle energy use (B1–B4/R1–R4). The loops are balancing if energy spending increases relative to gross regional product (GRP), e.g., if energy spending/GRP increases, GRP decreases; thus, employment decreases, which decreases building energy use by decreasing nonresidential sq ft (B1) and by decreasing net migration and population, which decreases dwelling units (B2) as well as VMT and vehicle energy use (B3), which complete the loop by decreasing energy spending. Similarly, if energy spending/GRP increases, GRP decreases, VMT per capita decreases, which decreases VMT and vehicle energy use (B4), opposing the original increase in energy spending. All four of these loops become reinforcing (R1–R4) if energy spending decreases relative to GRP, leading to higher GRP and further decrease in energy spending as a share of GRP. Additional reinforcing loops cause GRP to grow by increasing employment (R5) and nonresidential sq ft (R6). On the left side of the diagram, congestion and mode choice form additional balancing loops: if VMT increases, so does congestion, which leads people to drive less, reducing VMT (B5). Congestion also reduces VMT by increasing public transit and nonmotorized travel (B6) as well as fuel cost per VMT (B7). In Fig. 2, many of the drivers of energy use, such as VMT, public transit

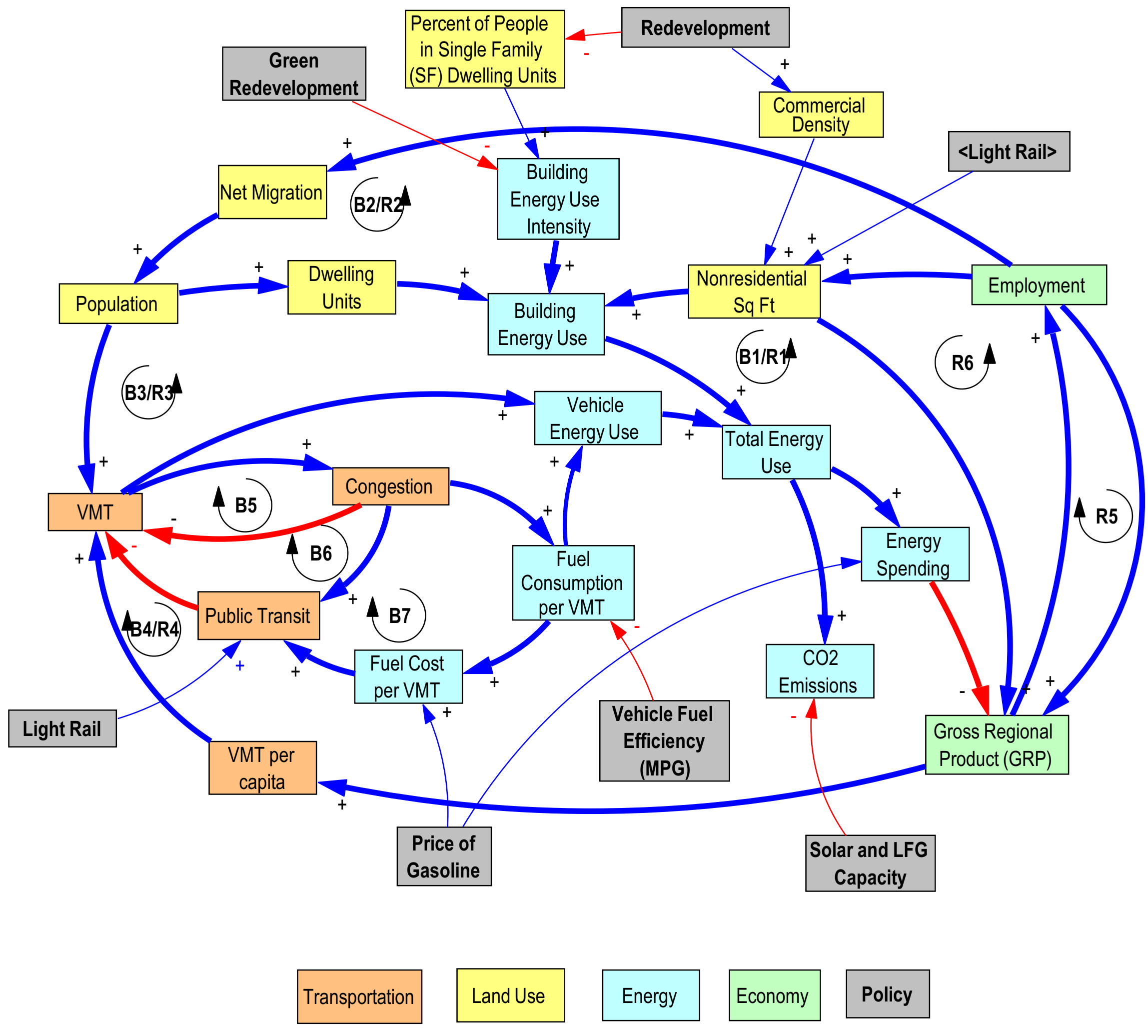

Fig. 2 Causal loop diagram (CLD) of relationships among variables in the energy sector, including links to variables from other sectors such as transportation and land use. These sectors are color coded as shown at the *bottom*. *Blue arrows* indicate positive associations; *red arrows* indicate inverse associations. *Gray boxes* indicate proposed sustainable development policies

ridership, and the building stock, are calculated in the transportation and land use sectors of the model, described in US EPA (2016). A detailed description of the energy sector, including calibration to historical data, is presented in Online Resource 1.

Modeled scenarios

The three main modeled scenarios (Business-as-Usual, Light Rail, and Light Rail + Redevelopment) are described in Table 1. Each scenario is modeled between the years 2000 and 2040, which matches the 2040 horizon used for regional planning (TJCOG 2013) as well as the Environmental Impact Statement for the Durham–Orange Light Rail (GoTriangle 2015). Beginning simulations in 2000 allows model calibration to historical data. Railway construction is proposed to begin in 2020, and so effects of the Light Rail scenarios develop after that year. Besides these scenarios, the model contains several energy policy and technology options. These include improved building and vehicle energy efficiency, higher solar capacity target, higher gasoline prices, and implementation of the federal Clean Power Plan. The building or vehicle efficiency options improve these efficiencies beyond national efficiency trends projected by the EIA Annual Energy Outlook (2015a). The solar capacity target in 2040 is a user-defined limit to solar capacity growth; based on North Carolina Sustainable Energy Association data (2015), the D–O LRP model default estimates conservatively that Tier 2 solar capacity will level off at 40 MW (megawatts) by 2020. We also explore scenarios with higher solar capacity, but in each case the growth rate is calibrated to historical solar capacity data and assumes growth slows as capacity approaches the target. The high gas price scenario assumes that the average gasoline price increased \$1 in 2016 (equal to its 2012 peak of \$3.52/gal) and then continues to

Table 1 Main modeled scenarios

Scenario	Abbreviation	Description
Business-as-Usual	BAU	Represents expected results if current demographic, land use, and transportation trends continue and serve as a baseline to contrast with the other scenarios described below. Neither Light Rail nor redevelopment is implemented
Light Rail	LR	Represents the implementation of the 17-mile Light Rail transit (LRT) line by 2026 between Durham and Chapel Hill and also deviates from the BAU scenario as follows:
		Assumes LRT motivates more people to use public transit than an equal number of bus service miles
		Assumes LRT increases usage of the entire public transit system, including buses
		Assumes a 10% increase in demand for developed nonresidential (excluding industrial) floor space in Tier 1 (station areas), gradually phased in during the 6-year period of Light Rail construction (2020–2026). This scenario as well as LR + R (below) does not differ from BAU before 2020
Light Rail + Redevelopment	LR + R	Represents the implementation of the LRT line with additional changes to zoning to encourage land redevelopment and increased density around the station areas. Redevelopment is the replacement or improvement of older buildings by newer structures
		Assumes 20% of station-area-developed land is redeveloped to almost three times its existing density by 2040, starting in 2020 in anticipation of the rail

increase by the same annual rate as in the BAU scenario, reaching \$5.23/gal by 2040 compared to \$3.74/gal in BAU 2040. All prices are in 2010 USD (US dollars). This scenario is a sensitivity test of gasoline price as well as a test of how the recent downward trend in gasoline price may be affecting regional energy usage. The Clean Power Plan scenario reflects EPA targets for reducing carbon emissions from fossil-fuel-fired power plants (US EPA 2015a, c). Although the plan gives states the option to achieve emission reductions through renewable energy standards or residential energy efficiency improvements, we focus the scenario on emission factor reductions from power plants. The scenario represents the North Carolina-specific goal (US EPA 2015b) of a linear 23% reduction in "ton CO_2 per kWh" between 2022 and 2030.

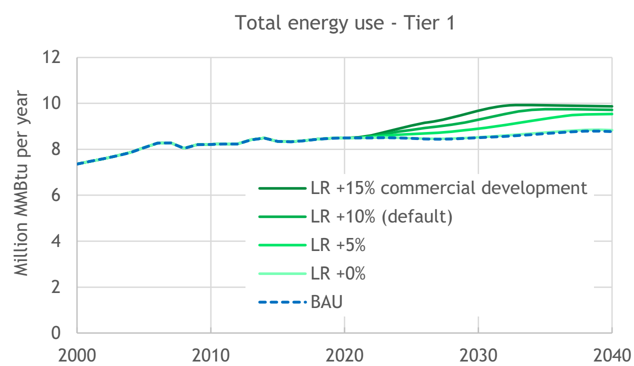

Fig. 3 Sensitivity of Tier 1 energy use to the assumed percent increase in commercial development due to Light Rail. The Light Rail scenario defaults to a 10% demand increase for retail, office, and service sq ft

Results

Impact of Light Rail scenarios on energy use

Contrary to our hypothesis, the Light Rail scenarios had higher regional energy use than Business-as-Usual (BAU) (Fig. 3) because the model assumes Light Rail stimulates demand for commercial development. Increased commercial (nonresidential) development in the model leads to population and economic growth (reinforcing loops R2 and R5 in Fig. 2), which increase regional energy use by increasing VMT (R3, R4) and the total building stock (R1, R2). We connected Light Rail and demand for nonresidential development because the local transit planning agency asserted that Light Rail would encourage economic development in the station areas; however, the magnitude of this development is unknown. By default, the model assumes a 10% increase[2] in demand for Tier 1 retail, office, and service sq ft in the Light Rail and Light Rail + Redevelopment scenarios. Varying this assumption between 0 and 15% reveals a similar range of total energy use outcomes (Fig. 3). In the Light Rail scenario with 0% change in commercial development demand, total energy use at Tier 1 is only 0.7%

[2] This increase is gradually phased in during the 6 years of Light Rail construction (2020–2026). Ten percent was chosen to be a conservative estimate of how Light Rail affects commercial development. Property values of businesses near rail stations are known to increase (Cervero and Duncan 2002; Garrett 2004). Light Rail can also stimulate economic activity; a report about the Dallas Area Rapid Transit (DART) Light Rail line (Clower et al. 2014) calculates that public spending of \$4.7B on rail line expansion between 2003 and 2013 resulted in \$7.4B of regional economic activity (transactions or spending) over that time period.

higher[3] than BAU in 2040, showing that almost all of the increase in total energy use is due to commercial development, not the Light Rail itself. With 5 and 15% demand increase, energy use is 8.6 and 12% higher than BAU in 2040, respectively. The demand increase leads to a larger building stock, which represents commercial activity and stimulates GRP growth and more miles traveled by vehicles (reinforcing loops R2–R6 in Fig. 2), both of which represent more energy use. In the default Light Rail scenario with 11% higher Tier 1 energy use than 2040 BAU, 80% of that energy growth came from increased building stock, 14% from vehicles (increased VMT), and 6% from Light Rail itself.[4] In summary, energy and emissions outcomes from the model must be interpreted as a reflection of how much economic growth the Light Rail would produce.

Assuming Light Rail scenarios stimulate 10% higher demand for commercial floor space, the model indicates that regional energy use increases relative to the Business-As-Usual scenario at both geographic tiers (Tier 2 = DCHC MPO; Tier 1 = Light Rail station areas). In the BAU scenario, total energy use at Tier 2 is projected to increase from 56 to 79 million MMBtu/year between 2000 and 2040 (Fig. 4a). In 2040, the Light Rail and Light Rail + Redevelopment scenarios have 3.8 and 5.3% higher energy use than BAU, respectively. Compared to the Light Rail scenario, energy use growth is higher in Light Rail + Redevelopment because it assumes a portion of land is redeveloped to a higher maximum density in the station areas, which allows more of the default 10% demand increase to be met.

These Tier 2 CO_2 emissions outcomes reflect these energy use increases, with 4.4 and 6.2% higher emissions in the Light Rail and Light Rail + Redevelopment scenarios compared to BAU in 2040. The emissions increases are proportionately larger than the energy use increases because building energy use increases proportionately more than vehicle energy use. In the D–O LRP model, building energy use (electricity and thermal combined) has higher emissions intensity (CO_2/MMBtu) than vehicle energy use.

Impacts of the Light Rail scenarios on energy use are proportionally larger at Tier 1, which uses 1/8–1/9 the energy of Tier 2 and has 1/9–1/12 the population, but surrounds the Light Rail stations. In the BAU scenario, total energy use at Tier 1 is projected to increase from 7.4 to 8.8 million MMBtu/year between 2000 and 2040 (Fig. 4b). In 2040, the Light Rail and Light Rail + Redevelopment scenarios have 11 and 25% higher energy use than BAU, respectively. The two Light Rail scenarios also have 12 and 29% higher CO_2 emissions, respectively, than BAU in 2040. Although Tier 1 is projected to have higher percentage change in energy and emissions due to the Light Rail scenarios, the absolute increase is larger at Tier 2. This is due to projected growth in VMT and building stock both inside and outside of Tier 1, as a result of rail.

[3] Energy use increases slightly despite the 0% demand increase, due to a positive feedback involving employment, earnings, population, and nonresidential sq ft growth.

[4] All electricity use for Light Rail is attributed to Tier 1.

Impact of Light Rail scenarios on VMT

The D–O LRP model projects that the Light Rail scenarios reduce VMT near Light Rail stations (Tier 1) in the short run but, contrary to our hypothesis, increase it in the long run (Fig. 5a). Tier 1 VMT decreases below the BAU scenario in 2026–2028, followed by a long-run increase in VMT due to economic growth stimulated by rail (reinforcing loop R6 in Fig. 2), and the assumption that as GRP per capita increases, people drive more (arrow between GRP, VMT per capita, and VMT in Fig. 2). At a regional scale (Tier 2, not shown), the D–O LRP model projects that VMT is 1 and 2% higher than BAU in 2040 in the Light Rail and Light Rail + Redevelopment scenarios, respectively. Tier 2 VMT is 7.6 billion miles/year in 2040 in the BAU scenario. The slight increase in VMT in the Light Rail scenarios translates into higher energy and CO_2 emissions from passenger vehicles, despite a national trend of increased passenger vehicle fuel efficiency. Light Rail does decrease the intensity of driving (Fig. 5b); Tier 1 VMT per capita is 3.1 miles/person/day lower in the Light Rail scenario, and 4.2 miles/person/day lower in the Light Rail + Redevelopment scenario, compared to BAU in 2040. At Tier 2, VMT per capita is 0.20 and 0.33 miles/person/day lower in Light Rail and Light Rail + Redevelopment, compared to BAU in 2040.

CO_2 emissions disaggregated by source

The main sources of CO_2 emissions in the Tier 2 region are building electricity use, passenger vehicles, and building natural gas use (Fig. 6). These represented 56, 33, and 9.4% of total regional emissions in 2015, respectively (gray bars). In the BAU scenario, the share of total CO_2 emissions from building electricity use increases to 62% in 2040, while the share from passenger vehicles decreases to 26% (blue bars). Despite an increase in VMT, total CO_2 emissions from passenger vehicles decrease between 2015 and 2040 in BAU due to an exogenous projection of increased miles per gallon (MPG) of gasoline (US EIA 2015a). By stimulating economic growth and land development, the Light Rail scenario increases the share from building electricity use to 63% by 2040 (green bars.) Water treatment and distribution, bus operation, and Light Rail operation each contribute less than 1% of regional CO_2 emissions. The distribution of emissions in the Light Rail + Redevelopment scenario (red bars) is very similar to the Light Rail scenario in 2040, with 63% of CO_2 emissions from building electricity use, 25% from passenger vehicles, and 11% from building natural gas use.

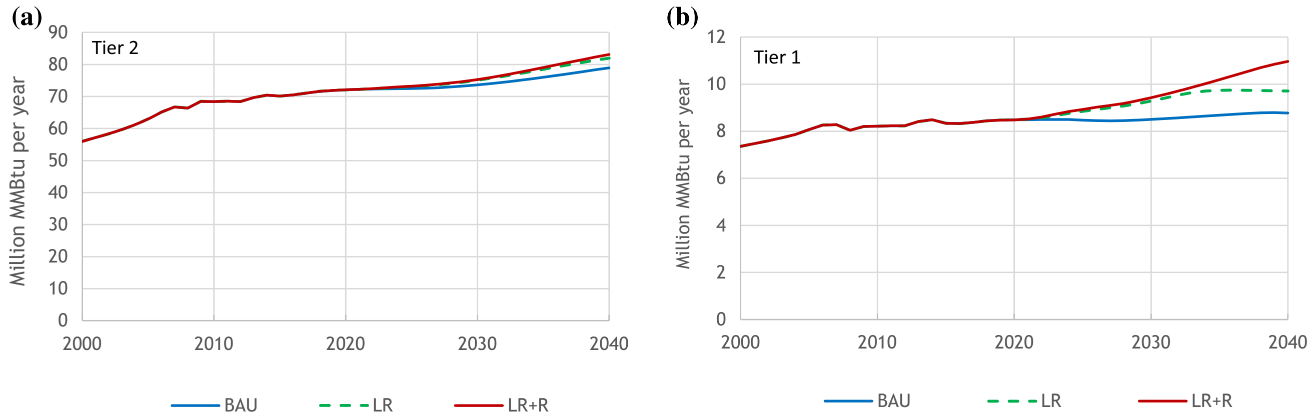

Fig. 4 Total energy use in scenarios with and without Light Rail at (**a**) Tier 2 and (**b**) Tier 1

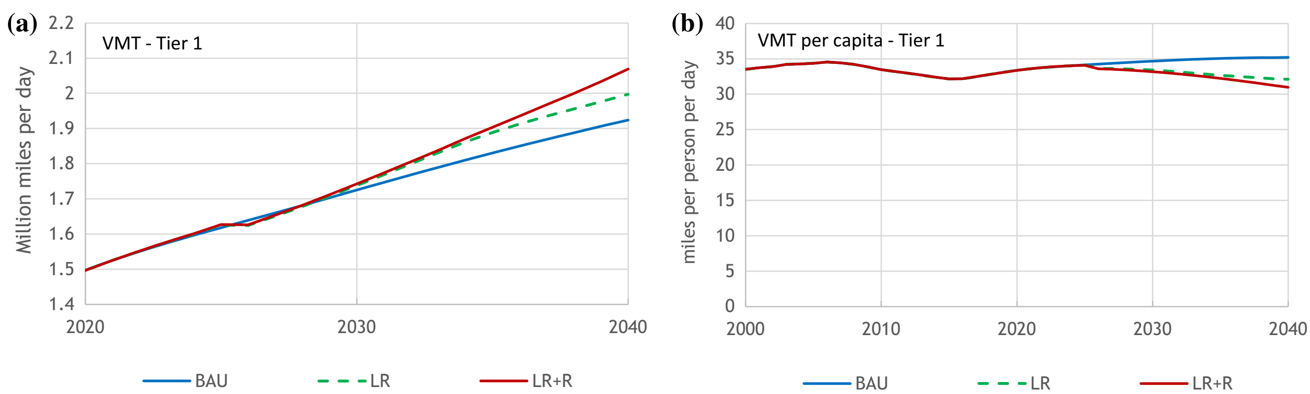

Fig. 5 (**a**) VMT and (**b**) VMT per capita at Tier 1. Note that (**a**) shows years 2020–2040 and the vertical axis is re-scaled to highlight short-term versus long-term behavior of VMT

External versus local influences on emissions

To compare the impact of local actions versus external influences on CO_2 emissions, modeled scenarios are shown with historical data in Fig. 7. Consistent with our hypothesis, external trends, such as building and vehicle efficiency improvement (Fig. 7a), and the federal Clean Power Plan (Fig. 7b), have a larger projected effect on regional emissions (Tier 2) than does Light Rail. This depends of course on the assumptions of our study, especially the projected trends in building and vehicle energy efficiency, and the amount by which Light Rail would stimulate GRP. In addition, building and vehicle efficiency improvement can happen due to both local and external actions: local choices on which products to install or buy, and external technology efficiency trends. With no building or vehicle energy efficiency improvement, CO_2 emissions in Tier 2 would grow 46% between 2005 and 2030 (Fig. 7a, pink line), while it grows only 27% over that time if building and vehicle efficiency improvements are assumed (BAU, blue line). About 60% of this emission reduction is due to MPG improvement, and about 40% is due to building energy efficiency improvement.[5] CO_2 emissions would grow 34% with MPG improvement but constant building energy intensity (bright red line). Light Rail scenarios slightly increase regional CO_2 emissions due to their stimulation of economic growth. By 2040, the Light Rail and Light Rail + Redevelopment scenarios have 4.4 and 6.2% higher emissions, respectively, than BAU. Among the scenarios in Fig. 7b, a scenario with the Clean Power Plan (CPP), higher gasoline prices, and without Light Rail would produce the lowest CO_2 emissions (bright blue line), returning to 2006 levels by 2030. Modeled CO_2 emissions between 2007 and 2012 differ from historical data (dashed line) by <5% on average (mean absolute percent error).

CO_2 emissions sensitivity to key energy sector variables

The relative influence of local and external activities on CO_2 emissions in the model can also be seen through sensitivity

[5] These include a 14% reduction in residential energy use intensity (EUI), an 11% reduction in commercial and industrial EUI, as well as an 80% increase in average vehicle MPG between 2015 and 2040.

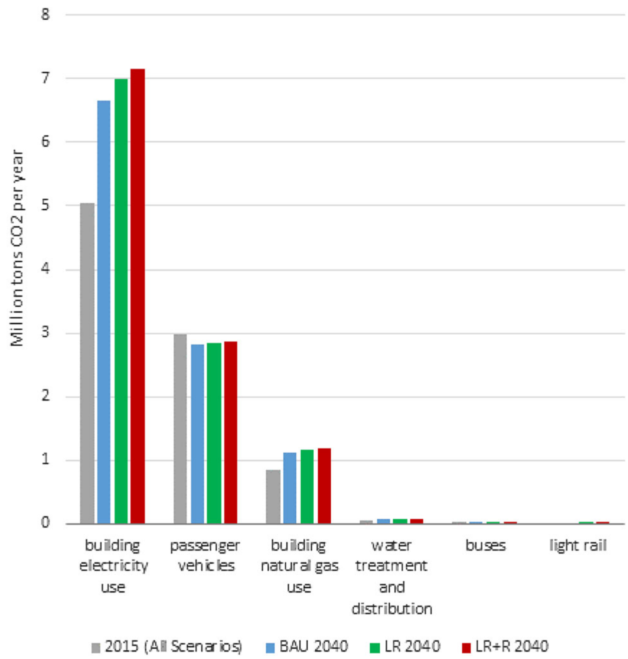

Fig. 6 Regional (Tier 2) CO_2 emissions by source: 2015 and 2040. CO_2 emissions are attributed to energy use in the Tier 2 geographic region, regardless of where the energy was generated

testing (Table 2). In this table, a linear ±10% change in key energy sector input variables is made between 2017 and 2040, and resulting changes in year 2040 model outputs are presented. Total CO_2 emissions at Tier 2 are most sensitive to a change in building energy intensity (energy use per sq ft), electricity CO_2 emissions factor, and MPG, in that order. Decreasing building energy intensity by 10% decreases emissions by 7.2%, while decreasing electricity emissions factor by 10% decreases emissions by 6.3%. (The Clean Power Plan essentially attempts to decrease electricity emissions factor, the amount of CO_2 emitted per unit electricity used) Increasing MPG by 10% decreases emissions by 1.9%. Emissions are proportionately less sensitive to changes in gasoline price, solar capacity, and Light Rail ridership, with a 10% change in these causing a 0.4–0.01% change in regional CO_2 emissions.

The output sensitivity to energy variables such as electricity emissions factor or MPG is due to relative size of these energy uses—most CO_2 emissions in the model come from building electricity use, followed by vehicle gasoline consumption (Fig. 6). Regional emissions are relatively insensitive to solar capacity because it currently fills a small fraction of community energy use, despite it being modeled as carbon neutral. Solar capacity would need to grow about tenfold to fulfill more than a few percent of community energy use.

Table 2 also presents cross-sector effects resulting from changes in energy use variables. One major synergy is that besides decreasing CO_2 emissions substantially, a 10% decline in building energy intensity also boosts gross regional product nearly 1%, because it lowers energy spending. One trade-off is that although 10% higher MPG reduces CO_2 emissions and boosts GRP, it also increases VMT and congestion as side effects of economic growth. Increasing gasoline price also presents a trade-off, because it reduces CO_2 emissions, VMT, and congestion, but also reduces GRP. Although the model incorporates elasticities such as a negative effect of gasoline price on VMT (loop B7

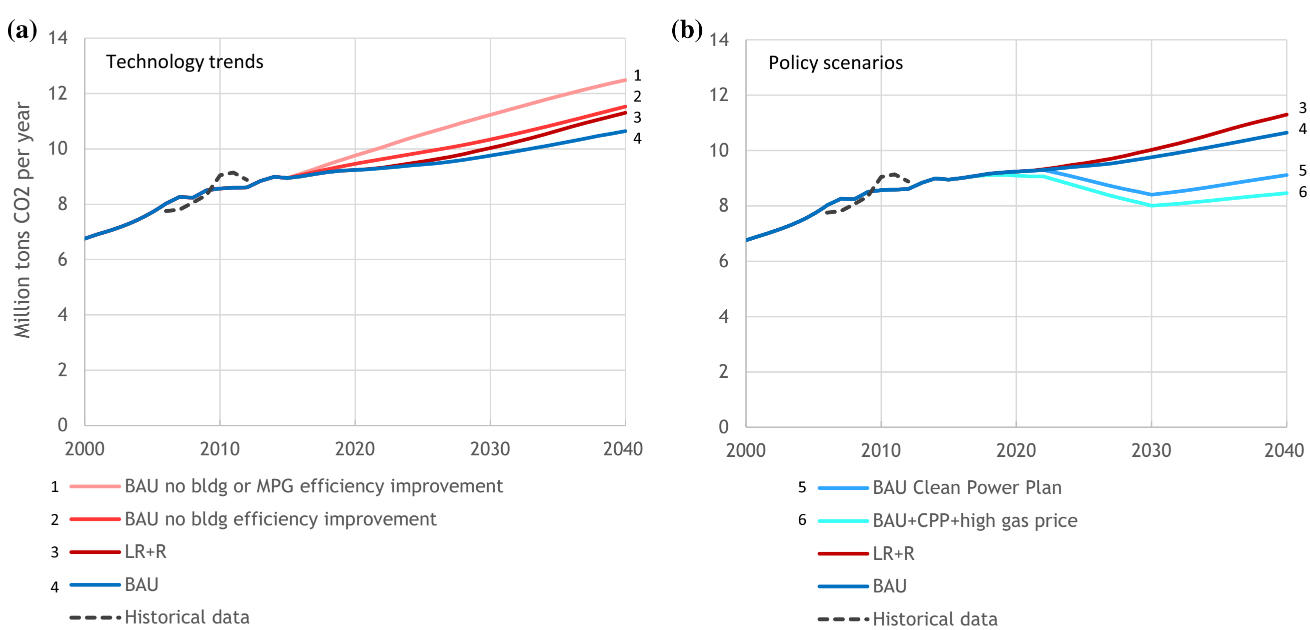

Fig. 7 Regional CO_2 emissions (Tier 2) in response to projected **(a)** trends in building and vehicle energy efficiency and **(b)** scenarios related to Light Rail or emissions reduction policies. Scenarios are numbered for reference

Table 2 Sensitivity* of model outputs to key energy variables at Tier 2

Scenario	CO2 Emissions	VMT	Congestion	Gross Regional Product	Nonresidential sq ft
Building energy intensity -10%	-7.21%	0.14%	0.14%	0.67%	0.27%
Electricity emissions factor - 10%	-6.32%	0.00%	0.00%	0.00%	0.00%
BAU	-5.79%	-1.86%	-1.86%	-7.92%	-8.72%
MPG +10%	-1.89%	1.17%	1.17%	0.39%	0.12%
LR (no redevelopment)	-1.63%	-0.66%	-0.66%	-1.60%	-2.33%
Gasoline price +10%	-0.37%	-1.18%	-1.18%	-0.38%	-0.04%
Solar capacity +10%	-0.03%	0.00%	0.00%	0.00%	0.00%
Light Rail ridership +10%	-0.01%	-0.03%	-0.03%	0.00%	0.00%
LR + R	0.00%	0.00%	0.00%	0.00%	0.00%
Light Rail ridership -10%	0.01%	0.03%	0.03%	0.00%	0.00%
Solar capacity -10%	0.03%	0.00%	0.00%	0.00%	0.00%
Gasoline price -10%	0.45%	1.29%	1.29%	0.44%	0.13%
MPG -10%	2.35%	-1.27%	-1.27%	-0.41%	-0.04%
Electricity emissions factor + 10%	6.32%	0.00%	0.00%	0.00%	0.00%
Building energy intensity +10%	7.23%	-0.13%	-0.13%	-0.60%	-0.18%

* Changes in model outputs are relative to 2040 values in the LR+R scenario. *Blue* indicates a reduction; *orange* indicates an increase. Energy variables are changed by 10% linearly between 2017 and 2040. Scenarios are sorted by CO_2 emissions. The BAU and LR scenarios are included for reference

in Fig. 2) and feedbacks such as the balancing feedback of energy spending on GRP (loop B1 in Fig. 2), a 10% change in major energy variables yielded less than 2% change in these cross-sector indicators by 2040. Other sectors of the model including land use (represented by nonresidential sq ft), transportation (represented by VMT and congestion), and economy (represented by GRP) are therefore relatively insensitive to a 10% change in these energy variables. The cross-sector indicators have much higher contrast between Light Rail scenarios and BAU. Compared to the Light Rail + Redevelopment scenario, the Light Rail and BAU scenarios have 1.6 and 7.9% lower GRP in 2040, respectively. Table 2 presents these scenarios in reference to Light Rail + Redevelopment because if built, Light Rail would likely be accompanied by redevelopment.

Balancing economic growth effects of Light Rail with renewable energy

Because North Carolina has a thriving solar industry, expanding local solar capacity is one strategy for mitigating the increase in CO_2 emissions from Light Rail-induced economic growth. Conservatively the model assumes that Tier 2 solar capacity plateaus at 40 megawatts (MW). Although solar capacity would need to grow tenfold to supply more than a few percent of energy use in the DCHC MPO region, this scenario is possible. If solar capacity grew to 640 MW, this would counteract the increase in CO_2 emissions in the Light Rail + Redevelopment scenario, compared to BAU in 2040[6] (Fig. 8). This amounts to a 29-fold increase in solar capacity within the Durham–Orange county area, which was 22 MW as of 2014. Statewide, North Carolina had about 1.75 GW solar capacity as of March 2016 (NC Sustainable Energy Association 2016) and total statewide potential capacity has been estimated as 22 GW, assuming maximized residential and commercial rooftop use, plus barren land and parking lots (Kaplan and Ouzts 2009). Although 640 MW is a high local target (Figure S2A), solar capacity at Tier 2 has had a compound annual growth rate of 2.75 between 2005 and 2014 (Figure S2B). If that rate were maintained, it would take four more years to reach 640 MW. The D–O LRP model assumes solar capacity growth slows proportionally to its distance from a target, so it projects 640 MW is reached by about 2025. That solar capacity equals 9–12% of regional building electricity use.

Impact of "green redevelopment" near rail stations

Redevelopment at Tier 1 presents the opportunity to replace or improve older buildings to become newer, more energy-efficient and water-efficient buildings, another strategy to mitigate the energy demand from rail-induced growth. The Light Rail + Redevelopment scenario in the model assumes redevelopment begins in 2020 in anticipation of the Light Rail; and by 2040 about a third of Tier 1 dwelling units and commercial/industrial square feet are redeveloped. If all redeveloped buildings had 25% lower energy intensity and 15% lower water intensity than in BAU,[7] this would decrease annual building energy use at Tier 1 by 7.7% in 2040 (including nonredeveloped buildings). The D–O LRP model projects that this would also

[6] 640 MW assumes a solar capacity factor of 0.15 for North Carolina. This is the ratio of actual power output to installed (nameplate) capacity over a year.

[7] equivalent to LEED Gold standard, with the water savings representing 60% of the 25% energy savings, http://www.usgbc.org/articles/green-building-facts.

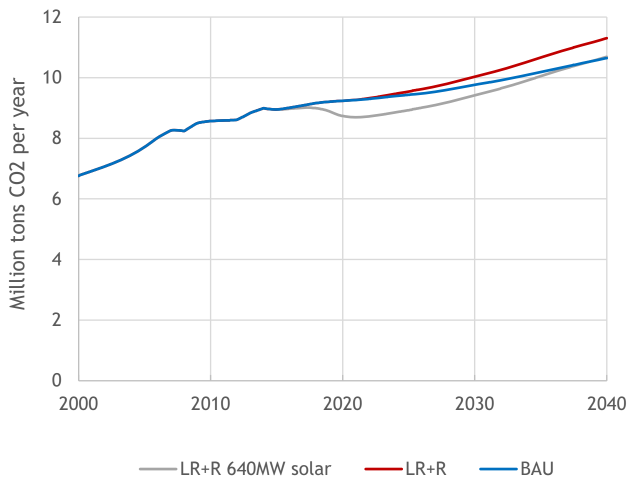

Fig. 8 Regional CO_2 emissions, with impact of aggressive solar capacity development shown in gray. If solar capacity grew to 640 MW, by 2040 this would counteract the increase in CO_2 emissions due to Light Rail + Redevelopment, compared to BAU

increase Tier 1 GRP by 1.5% by 2040 due to reduced energy costs, which in effect increase the purchasing potential of households and businesses. This green redevelopment strategy would keep total energy use at Tier 1 below that in the Light Rail scenario between 2020 and 2034; from 2035 onward total energy use would surpass the Light Rail scenario but remain below Light Rail + Redevelopment.

Regional energy spending, with feedback to regional economy

As of 2015, Tier 2 GRP was $31 billion/year (all modeled dollars are 2010 US dollars). Energy spending equaled 4.6% of GRP or $1.4 billion/year.[8] The model projects that the electricity cost for Light Rail operation—$1.3 million/year in 2026 and $1.6 million/year by 2040—is less than 0.1% of the regional energy budget. The regional energy budget decreases as a fraction of GRP, reaching 3.7% of GRP in the 2040 BAU scenario due to improved building and vehicle energy efficiency despite increasing electricity, natural gas, and gasoline prices in real terms. Although regional energy spending in 2040 is higher in the Light Rail scenarios than BAU, energy spending drops to 3.6% of GRP in Light Rail scenarios due to their faster GRP growth compared to energy-spending growth. The model also assumes negative feedback between energy spending/GRP and GRP, relative to an equilibrium in year 2000 (balancing loop B1/R1 in Fig. 2). Therefore, in BAU the decrease in energy spending/GRP between 2000 and 2040 increases GRP about 1.5% in 2040. This feedback effect is slightly larger in the Light Rail scenarios, boosting GRP 1.8% in 2040.

We note that although the model contains many balancing loops with delays, such as between energy spending/GRP and GRP, the model does not have noticeable oscillations because these feedback effects are much smaller than the overall growth (reinforcing loop) effects of population and land development. The same is true for the delayed balancing loop between congestion and VMT; because modeled congestion reduces VMT by <1%, other factors such as fuel price, population growth, and vehicle ownership drive VMT without oscillations. Although these feedbacks are small percentages, they are large quantities; 1% of VMT is still tens of millions of miles reduced annually. Likewise the 1.5% energy-spending feedback on GRP in 2040 represents an $890 million larger economy.

Decomposition of CO_2 emissions into relative indicators at Tier 2 (regional scale) and Tier 1 (near station areas)

CO_2 emissions can be explained as the product of population, GRP per capita (individual wealth), energy use per GRP (energy intensity of the economy), and CO_2 per unit energy use (emissions intensity of the energy system). Growth or reduction in CO_2 emissions can be attributed to an increase or decrease in each of these relative indicators, or "Kaya factors" (Dhakal and Kaneko 2002; Raupach et al. 2007). Population and average individual wealth are projected to increase at both Tiers, and Light Rail + Redevelopment (LR + R) may further increase both factors (Fig. 9). Tier 1 population is projected to grow 75% between 2000 and 2040 in LR + R compared to 43% in BAU. At Tier 2, these numbers are 98 and 92%, respectively. Tier 1 GRP per capita grows 82% between 2000 and 2040 in LR + R compared to 75% in BAU. At Tier 2, these numbers are 51 and 43%. Energy intensity of the economy decreases about 50% between 2000 and 2040 at both Tiers, due to improvements in building and vehicle energy efficiency. LR + R further decreases energy use/GRP about one percentage point at both Tiers. Emissions intensity of energy use increases about 10% between 2000 and 2040 at both Tiers. LR + R slightly increases emissions intensity at both Tiers by stimulating growth of building energy use more than transportation energy use. Modeled building energy use has about double the emissions intensity (per MMBtu consumed) than transportation energy use. To summarize, projected CO_2 emissions growth at both Tiers is primarily driven by increased population and increased GRP per capita and driven slightly by growth in building energy use (which is more emissions intensive than vehicle energy use). CO_2

[8] As with CO_2 emissions, the model attributes energy spending for all fuel types (electricity, gasoline, etc.) to energy use in the DCHC MPO region, regardless of where the energy was generated or where the emissions were produced (for example, in a power plant outside the region).

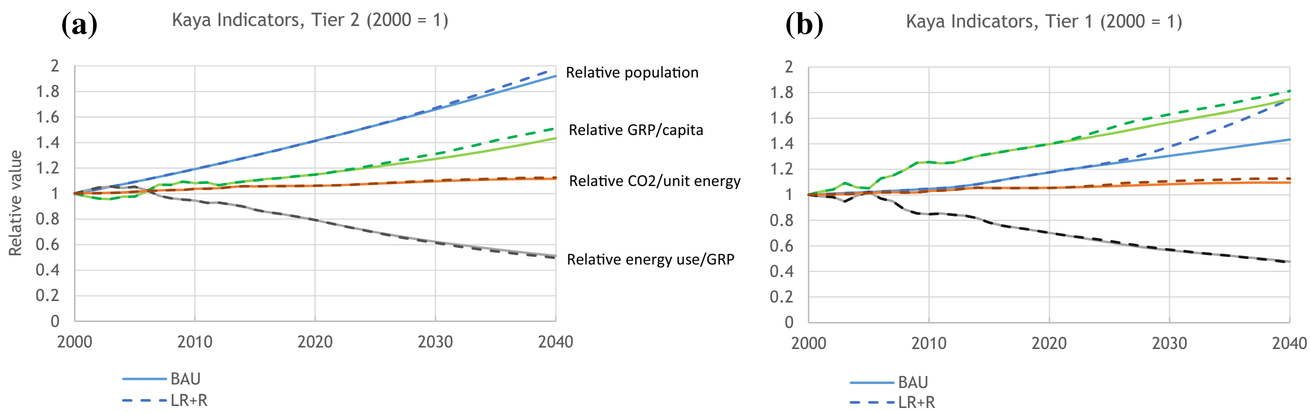

Fig. 9 Decomposition of CO_2 emissions into relative indicators (year 2000 = 1) at **a** Tier 2 and **b** Tier 1. The indicators are population (*blue*), GRP per capita (*green*), energy use per GRP (*gray*), and CO_2 per unit energy (*orange*) at both Tiers. Regional CO_2 emissions are the product of these four indicators. *Solid lines* indicate the BAU scenario; dashed lines indicate Light Rail + Redevelopment

emissions growth is mitigated by declining energy use per GRP due to energy efficiency improvements in buildings and vehicles.

Discussion

In this paper we explored how system dynamics modeling can contribute to a stakeholder discussion of regional sustainability anchored on the decision to build Light Rail. Our model projects that Light Rail scenarios increase energy use and CO_2 emissions in the long term, but slightly reduce the emissions intensity of the economy. These results are dependent on the assumed economic growth stimulated by Light Rail, at the scale of a Metropolitan Planning Organization (MPO). By modeling regional energy use, the model quantifies the relative impact of different management options, such as building and vehicle energy efficiency, solar capacity, and emissions regulation for electricity generation.

Growth effects of Light Rail

A common argument for building Light Rail is that it stimulates the economy (De Bruijn and Veeneman 2009). For example, commercial property values are expected to increase near Light Rail stations (Debrezion et al. 2007; Cervero and Duncan 2002). The amount of economic growth stimulated by Light Rail is a key uncertainty in determining energy, emissions, and other downstream effects of the proposed Durham–Orange Light Rail. By default, the Light Rail scenarios of the D–O LRP model assume a 10% increase in demand for nonresidential sq ft at Tier 1 (the station areas). However, if this is changed to zero increase in demand, GRP at Tier 2 (the Metropolitan Planning Organization boundary) increases less than 2% from BAU[9] in the Light Rail scenarios by 2040. Conversely, if we assume Light Rail increases the demand for nonresidential sq ft by 15%, GRP increases by 7% and 10% in the Light Rail and Light Rail + Redevelopment scenarios, respectively, by 2040. That translates into 7% higher energy use in the Light Rail + Redevelopment scenario (Fig. 3), which results from population growth, more dwelling units, and slightly higher VMT. In the default setting of 10% increase in nonresidential demand, the Light Rail and Light Rail + Redevelopment scenarios had 3.8% and 5.3% higher energy use than BAU in 2040, respectively (Fig. 4a), and CO_2 emissions were 4.4 and 6.2% higher than BAU in 2040, respectively.

The Light Rail scenarios are projected to cause a short-term decline in VMT followed by a long-term increase (Fig. 5a). Population and economic growth stimulated by rail leads to the long-term increase in VMT, resulting in higher vehicle energy use. The intensity of driving decreases, however, with VMT per capita decreasing 3–4 miles/person/day in the Light Rail scenarios relative to the BAU scenario in 2040 at Tier 1 (Fig. 5b). This happens despite an increase in average wealth (GRP per capita) in the Light Rail scenarios (Fig. 9) which increases driving behavior in our model.

To place the growth effects of Light Rail in perspective, the electricity used to power the Light Rail itself would be less than 0.1% of the regional energy budget, and the CO_2 from this electricity use would be about 0.1% of regional CO_2 emissions (Fig. 6). Note that these are use-phase emissions, which do not include emissions attributed to Light Rail construction. If these life-cycle emissions are

[9] When the increase in demand for nonresidential sq ft by LRT is set to zero, there is still a slight increase in GRP, especially in the Light Rail + Redevelopment scenario, due to a positive feedback loop involving growth in employment, earnings, total population, and nonresidential sq ft.

included and assumed to be 70% larger than those from Light Rail operation (Chester et al. 2010), building and operating the Durham–Orange Light Rail would still represent less than 0.3% of Tier 2 annual CO_2 emissions. The indirect and cumulative impacts of Light Rail on regional energy use and emissions—by stimulating population growth, land development, economic growth, and automobile usage—are therefore much larger than the direct impacts of Light Rail alone, according to the model projections.

Although the economic growth stimulated by Light Rail increases CO_2 emissions, the economy is actually projected to be less emissions intensive in the Light Rail scenarios. By 2040, CO_2 emissions per unit GRP are 2.3% lower than BAU in the Light Rail and Light Rail + Redevelopment scenarios at Tier 2. This is partly explained by lower energy intensity of GRP (energy use/GRP) in the Light Rail scenarios compared to BAU (Fig. 9). The Light Rail scenarios have lower energy use/GRP because they increase GRP growth slightly more than proportional to their increase in regional energy use. In all scenarios, the economy is also projected to become less energy and emissions intensive due to improvements in building and vehicle energy efficiency. In the BAU and Light Rail scenarios, CO_2 emissions/GRP decline more than 40% between 2000 and 2040.

Regional strategies for reducing energy use and emissions

If implemented, the federal Clean Power Plan would be a major boost toward achieving regional emissions goals. It would move the region closer to the Durham GHG Plan's 2030 goal of 30% GHG emissions reduction from a 2005 baseline. (At Tier 2 this represents 5.4 million tons CO_2/year compared to 7.7 million in 2005.) The D–O LRP model applies Clean Power Plan emissions reduction goals specific to North Carolina (US EPA 2015b), representing a linear 23% reduction in "ton CO_2 per kWh" (electricity emission factor) between 2022 and 2030. This scenario would achieve 24% of progress toward the Durham plan's 2030 goal, relative to a 2030 BAU scenario with no building or vehicle energy efficiency improvement after 2015 (Fig. 7a, b). Since the Clean Power Plan specifies CO_2 emission factor reductions from electricity generation up to 2030, further technology and policy goals are needed after 2030 to continue reducing annual CO_2 emissions in the context of population growth.

Solar capacity expansion is one local strategy for further reducing CO_2 emissions attributed to regional energy use. Current solar capacity in Durham and Orange counties is about 22 MW (North Carolina Sustainable Energy Association 2015) and has increased nearly threefold annually, on average, between 2005 and 2014. If solar capacity grew to 640 MW by 2040, this would counteract the increase in CO_2 emissions due to the Light Rail + Redevelopment scenario, compared to BAU (Fig. 8). This represents an emissions reduction in about 600,000 tons CO_2/year by 2040. Assuming the historical growth rate of solar capacity is maintained intrinsically, but slowed by a damping factor as it approaches the target, the model projects that 640 MW is reached by 2025 (Figure S1A), with solar electricity representing 9–12% of regional building energy use.

Redevelopment near the proposed rail stations (Tier 1) presents an opportunity to replace or improve older buildings to become newer, more energy-efficient buildings, further reducing emissions. In the Light Rail + Redevelopment scenario, about one-third of Tier 1 housing and commercial/industrial floor space is redeveloped by 2040. If all Tier 1 redevelopment met LEED Gold (25% less energy intensity and 15% less water intensity than BAU), by 2040 this would decrease total building energy use at Tier 1 by 7.7%. Energy-efficient redevelopment in the rail corridor could produce significant energy savings for Tier 1, but this only translates to a 0.7% reduction in Tier 2 energy use. To achieve significant energy savings for Tier 2, the existing building stock would need energy efficiency retrofits or energy-efficient redevelopment. Onat et al. (2014) reach the same conclusion regarding the US residential building stock, suggesting that either retrofitting or a combination of retrofitting and new energy-efficient homes is more effective at stabilizing emission growth than new green buildings alone. Onat et al. modeled retrofits that decrease residential energy intensity by 2/3.

Relative impact of regional actions and external influences

A main finding of our analysis is that national policies and technology trends would have a proportionately larger impact on the regional energy/emissions landscape than would regional actions such as building Light Rail. Light Rail scenarios could increase regional CO_2 emissions 2–3% by 2030 due to assumed stimulation of economic development. However, national trends in building and vehicle energy efficiency could account for 25% of progress[10] toward the Durham GHG emissions reduction goal by 2030. When these efficiency improvements are coupled with Clean Power Plan goals for North Carolina, they account for 49% of progress toward the Durham GHG

[10] Progress being measured as: emissions reduction due to action X/total emissions reduction between 2030 BAU and Durham GHG goal. In this case, the 2030 BAU assumes no building or vehicle energy efficiency improvements after 2015.

emissions reduction goal, relative to a 2030 BAU scenario with no building or vehicle energy efficiency improvement after 2015. Although gasoline price is a major uncertainty in the model, if it increased back to its 2012 high after 2016 (resulting in prices about $1.00–$1.50/gal above BAU thereafter), this could move the region another 6% toward the 2030 GHG reduction goal.

Limitations of the D–O LRP model

The accuracy of the model depends on scale and level of physical disaggregation (how many energy types and technologies are identified). The metropolitan (MPO) scale of the model is useful because (1) it is an administrative boundary for transportation planning, and (2) it is slightly larger than a county boundary, meaning the results could be adapted or compared to other counties. Some of the relationships in the model come from geographically larger models, so we assume the physical system behaves similarly at different scales. The feedback loops between energy spending and GDP are borrowed from global (Warr and Ayres 2006; Fiddaman 2002) and North American (Bassi 2009; Bassi et al. 2010) energy-economy models. Our model also makes simplifying assumptions about energy system disaggregation. Natural gas and electricity are the only fuel sources modeled within the building sector, though petroleum and biomass are also minor fuel sources in North Carolina (US EIA 2015b). We do not distinguish building uses such as cooking or lighting. Instead, the model serves to estimate the relative magnitudes of effects considered in community decisions—effects which depend largely on VMT, building stock, and energy intensity trends.

Policy implications and conclusion

With no building or vehicle energy efficiency improvement, the D–O LRP model projects CO_2 emissions in Tier 2 would grow 46% between 2005 and 2030, which is consistent with the 48% increase projected by the Durham GHG Plan over the same years. The Durham GHG Plan does not include improvements in building or vehicle energy efficiency in this business-as-usual scenario. By factoring in these efficiency improvements, our BAU scenario is a more optimistic projection of CO_2 emissions (27% increase between 2005 and 2030).

Although our analysis asks similar questions to the Environmental Impact Statement (EIS) for the Light Rail line, we explore the assumption that Light Rail creates economic growth, which leads to higher rather than lower energy consumption. Compared to our study, the EIS analyzes a larger portion of the Research Triangle region which includes populous Wake County, and concludes that Light Rail will reduce regional energy use by 0.06% or 83 billion BTUs (compared to the no-rail scenario in 2040), but this is only within transportation energy use and does not include effects on buildings (GoTriangle 2015). This is consistent with transportation literature, which emphasizes transit effects on private vehicle energy use but not building energy use (Gallivan et al. 2015, Transportation Research Board 2009). By assuming that Light Rail induces economic growth, increasing building stock, and VMT, our analysis suggests that Light Rail will increase regional energy use by 3000 billion BTUs compared to BAU in 2040 or by 4200 billion BTUs if Light Rail is combined with redevelopment. This is a 4.4 and 6.2% increase in Tier 2 emissions, respectively. We suggest that building energy use resulting from economic development would be a useful addition to indirect and cumulative impacts within future Environmental Impact Statements for transportation projects.

Our finding that Light Rail could slightly increase regional energy use and CO_2 emissions can be weighed in context of the rail's regional benefits. Our previous analysis suggests Light Rail scenarios could lead to higher non-motorized travel per capita, which has health benefits (US EPA 2016). The economy is also projected to be less energy and emissions intensive in the Light Rail scenarios compared to BAU, meaning a comparable amount of growth under BAU conditions would require more energy and produce more emissions. The effect is subtle and depends on how much economic growth occurs with Light Rail; an assumed 10% increase in demand for nonresidential floor space due to Light Rail leads to 2.3% lower CO_2 emissions per unit GRP by 2040, compared to Business-as-Usual. Light Rail scenarios are also expected to increase residential and commercial property values (Cervero and Duncan 2002; Debrezion et al. 2007), more than would higher-density building alone (US EPA 2016). With a growing regional population and potential for sprawling development, expanded public transportation such as Light Rail is a defensible strategy for concentrating growth, even if it has mixed effects on community energy use. Other researchers have recognized these trade-offs between economic development and emission reduction goals; like Development Impact Assessment [DIA, (Cox et al. 2015; Harrington and McConnell 2003)], our approach explores co-benefits and trade-offs among environmental, economic, and social outcomes.

Our analysis highlights that local factors such as increased solar capacity and green or retrofitted buildings, as well as national factors such as CO_2 emissions regulation and improved vehicle energy efficiency, could allow the region to achieve the economic benefits of Light Rail while minimizing environmental costs. By depicting outcomes as a time series, the D–O LRP model allows policymakers to consider the shape of trends, adding value to current analyses such as the Environmental Impact Statement for the Durham–Orange Light Rail and the Durham GHG Plan, which highlight one baseline year and one final year. The model also incorporates interactions between economy, transportation, land use, and energy, allowing policymakers to explore the combined effect of multiple actions, within a few seconds run time. Our analysis suggests that locally increased solar capacity could counteract energy and emissions growth due to Light Rail; however, progress toward regional emissions reduction goals such as the Durham GHG plan could be about ten times faster if the Clean Power Plan were enacted, or if projected national building and vehicle energy efficiency improvements occur.

We recommend local policies (such as tax incentives) that encourage LEED-certified buildings in the transit-oriented redevelopment area, that encourage solar capacity investment, and that encourage energy audits and efficiency retrofits to the existing building stock. Many of these policies were suggested in the Durham GHG Plan (ICLEI 2007), and the potential for transit-stimulated economic growth makes these policies increasingly necessary to meet GHG reduction goals. Tracking CO_2 emissions is a recent phenomenon, so cities may have limited or no data (Fong et al. 2009) yet projections of future CO_2 emissions must be anchored to historical data. Therefore, we support efforts to collect annual regional data on energy use and emissions from buildings and vehicles, because this will help stakeholders measure progress toward GHG reduction goals.

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References

Bassi A (2009) An integrated approach to support energy policy formulation and evaluation. PhD, Department of Geography, The University of Bergen

Bassi AM, Harrisson J, Mistry RS (2009) Using an integrated participatory modeling approach to assess water management options and support community conversations on Maui. Sustainability 1(4):1331–1348

Bassi AM, Powers R, Schoenberg W (2010) An integrated approach to energy prospects for North America and the rest of the world. Energy Econ 32(1):30–42. doi:10.1016/j.eneco.2009.04.005

Cervero R, Duncan M (2002) Transit's value-added effects: light and commuter rail services and commercial land values. Trans Res Rec J Transp Res Board 1805:8–15

Chester MV, Horvath A, Madanat S (2010) Comparison of life-cycle energy and emissions footprints of passenger transportation in metropolitan regions. Atmos Environ 44:1071–1079

Chester M, Pincetl S, Elizabeth Z, Eisenstein W, Matute J (2013) Infrastructure and automobile shifts: positioning transit to reduce life-cycle environmental impacts for urban sustainability goals. Environ Res Lett 8(1):015041. doi:10.1088/1748-9326/8/1/015041

City of Durham (2009) Durham landfill gas-to-energy green power project

Clower TL, Michael B, Owen W-C, Matthew G (2014) Through recession and recovery: economic and fiscal impacts of capital and operating spending by Dallas area rapid transit. http://www.dart.org/about/economicdevelopment/January2014DARTEconomicandFiscalImpacts.pdf

Cox S, Nawaz K, Sandor D (2015) Development impact assessment (DIA) case study: South Africa. National Renewable Energy Laboratory, Golden, CO

DCHC MPO, Triangle Transit Board of Trustees, and Durham Board of County Commissioners (2011) The Durham county bus and rail investment plan

De Bruijn H, Veeneman W (2009) Decision-making for light rail. Transp Res Part A 43:349–359

Debrezion G, Pels E, Rietveld P (2007) The impact of railway stations on residential and commercial property value: a meta-analysis. J Real Estate Financ Econ 35(2):161–180

Dhakal S, Kaneko S (2002) Urban energy use in Asian mega-cities: is Tokyo a desirable model?. Workshop of IGES/APN Mega-City Project, Kitakyushu, Japan

Duran-Encalada JA, Paucar-Caceres A (2009) System dynamics urban sustainability model for Puerto Aura in Puebla, Mexico. Syst Pract Action Res 22(2):77–99

Duke Energy (2008) Duke Energy Carolinas signs deal to turn landfill gas into energy. Duke Energy, Charlotte, NC

Ewing R, Bartholomew K, Winkelman S, Walters J, Chen D (2008) Growing cooler: the evidence on urban development and climate change. ULI-the Urban Land Institute, Washington, DC

Fiddaman T (2002) Exploring policy options with a behavioral climate–economy model. Syst Dyn Rev 8(2):243–267

Fiksel J, Bruins R, Gatchett A, Gilliland A, ten Brink M (2013) The triple value model: a systems approach to sustainable solutions. Clean Technol Environ Policy. doi:10.1007/s10098-013-0696-1

Fong W-K, Matsumoto H, Lun Y-F (2009) Application of System Dynamics model as decision making tool in urban planning process toward stabilizing carbon dioxide emissions from cities. Build Environ 44:1528–1537

Forrester JW (1969) Urban dynamics. MIT Press, Cambridge

Freid T (2015) Email message to authors on January 9

Gallivan F, Rose E, Ewing R, Hamidi S, Brown T (2015) Quantifying transit's impact on GHG emissions and energy use–the land use component. Transportation Research Board, Washington, DC

Garrett TA (2004) Light-rail transit: myths and realities. Bridges. Technical report, Federal Reserve Bank of St. Louis. https://www.stlouisfed.org/Publications/Bridges/Winter-20032004/Light Rail-Transit-Myths-and-Realities

GoTriangle (2015) Durham–orange light rail transit project draft environmental impact statement

GoTriangle (2016) Durham–Orange light rail transit project: combined final environmental impact statement and record of decision. Accessed April 28. http://ourtransitfuture.com/feis-

rod/. http://ourtransitfuture.com/wp-content/uploads/2016/02/F.1_Substantive-Public-Comment-and-Responses.pdf
Grubb T (2015) Neighbors question Farrington Road light-rail center plan. The news and observer, August 17, 2015. http://www.newsobserver.com/news/local/community/chapel-hill-news/article31506434.html
Han J, Hayashi Y (2008) A system dynamics model of CO_2 mitigation in China's inter-city passenger transport. Transp Res Part D 13:298–305
Harrington W, McConnell V (2003) A lighter tread? Policy and technology options for motor vehicles. Environment 45(9):22–36, 38–39
Hennessy G, Cook J, Bean M, Dykes K (2011). Economic dynamics for smarter cities. 29th International Conference of the System Dynamics Society, Washington, DC
ICLEI (2007) City of Durham & Durham county greenhouse gas and criteria air pollutant emissions inventory and local action plan for emission reductions. ICLEI Energy Services, Toronto, Canada
Kaplan S, Ouzts E (2009) Growing solar in North Carolina: Solar power's role in a clean energy future. Environment North Carolina Research & Policy Center, Raleigh, NC
Kenworthy JR (2008) Energy use and CO_2 production in the urban passenger transport systems of 84 international cities: findings and policy implications. In: Droege P (ed) Urban energy transition: from fossil fuels to renewable power. Elsevier, New York
Larivière I, Lafrance G (1999) Modelling the electricity consumption of cities: effect of urban density. Energy Econ 21:53–66
Nahlik MJ, Chester MV, Andrade L, Archer M, Barnes E, Beguelin M, Bonilla L, Bubenheim S, Burillo D, Cano A, Guiley K, Hamad M, Heck J, Helble P, Hsu W, Jensen T, Kirtley K, LaGrou N, Loeber J, Mann C, Monk S, Paniagua J, Prasad S, Stafford N, Kannappan BT, Unger S, Volo T, Watson M, Woodruff A (2014) The water, energy, and infrastructure co-benefits of smart growth planning in Phoenix, Arizona. Center for Earth Systems Engineering and Management, Arizona State University, Phoeniz, AZ
NC Sustainable Energy Association (2016) Market intelligence. Accessed April 28. http://www.energync.org/?page=MarketIntelligence
Newman PWG, Kenworthy JR (1989) Gasoline consumption and cities: a comparison of U.S. cities with a global survey. J Am Plann Assoc 55(1):24–37
North Carolina Sustainable Energy Association (2015) Installed Solar Projects in NC. Raleigh, NC
Onat NC, Egilmez G, Tatari O (2014) Towards greening the US residential building stock: a system dynamics approach. Build Environ 78:68–80
Organization, Durham Chapel Hill Carrboro Metropolitan Planning (2012) TRMv5 SE data for the preferred growth scenario. Accessed Oct 2014. http://www.dchcmpo.org/programs/transport/2040.asp
O'Toole R (2008) Does rail transit save energy or reduce greenhouse gas emissions?. The Cato Institute, Washington, DC
Raupach MR, Marland G, Ciais P, Le Quéré C, Canadell JG, Klepper G, Field CB (2007) Global and regional drivers of accelerating CO_2 emissions. Proc Natl Acad Sci USA 104(24):10288–10293
Rees W, Wackernagel M (1996) Urban ecological footprints: why cities cannot be sustainable–and why they are a key to sustainability. Environ Impact Assess Rev 16:223–248
Rickwood P, Glazebrook G, Searle G (2008) Urban structure and energy–a review. Urban Policy Res 26(1):57–81
Solar Energy Industries Association (2016) Solar spotlight: North Carolina. Washington, DC
Stave K (2002) Using system dynamics to improve public participation in environmental decisions. Syst Dyn Rev 18(2):139–167
Steemers K (2003) Energy and the city: density, buildings and transport. Energy Build 35:3–14
Sterman JD (2000) Business dynamics: systems thinking and modeling for a complex world. McGraw-Hill, New York
Sterman J, Fiddaman T, Franck T, Jones A, McCauley S, Rice P, Sawin E, Siegel L (2012) Climate interactive: the C-ROADS climate policy model. Syst Dyn Rev 28(3):295–305
Tidwell VC, Passell HD, Conrad SH, Thomas RP (2004) System dynamics modeling for community-based water planning: application to the Middle Rio Grande. Aquat Sci 66:357–372
TJCOG (2013) Imagine 2040: the triangle region scenario planning initiative final summary document
Transportation Research Board (2009) Driving and the built environment: the effects of compact development on motorized travel, energy use, and CO_2 emissions. National Research Council, Washington, DC
Triangle Regional Transit Program (2012) Alternatives analysis final report: Durham–Orange County corridor. Triangle Transit, Durham, NC
UN (2015) World urbanization prospects: the 2014 revision. Department of Economic and Social Affairs, Population Division, New York
US EIA (2009) 2009 RECS survey data. U.S. Energy Information Administration. Accessed 31 Aug. http://www.eia.gov/consumption/residential/data/2009/
US EIA (2015a) Annual energy outlook 2010–2015. U.S. Energy Information Administration. Accessed 19 Aug. http://www.eia.gov/forecasts/aeo/
US EPA (2015a) Carbon pollution emission guidelines for existing stationary sources: electric utility generating units. U.S. Environmental Protection Agency. Accessed 24 Aug. http://www2.epa.gov/sites/production/files/2015-08/documents/cpp-final-rule.pdf
US EIA (2015b) State energy data system (SEDS): 1960–2013 (complete). Accessed 28 April. http://www.eia.gov/state/seds/seds-data-complete.cfm?sid=NC
US EPA (2015b). Clean power plan: state at a glance: North Carolina. U.S. Environmental Protection Agency. Accessed 24 Aug. http://www.epa.gov/airquality/cpptoolbox/north-carolina.pdf
US EPA (2015c) Overview of the clean power plan: cutting carbon pollution from power plants. U.S. Environmental Protection Agency, Washington, DC
US EPA (2016) A system dynamics model for integrated decision making: the Durham–Orange light rail project. US Environmental Protection Agency, Washington, DC
Van Rooijen DJ (2009) Urbanization, water demand and sanitation in large cities of the developing world: an introduction to studies carried out in Accra, Addis Ababa and Hyderabad. Arcueil, France: 8th World Wide Workshop for Young Environmental Scientists
Warr B, Ayres R (2006) REXS: a forecasting model for assessing the impact of natural resource consumption and technological change on economic growth. Struct Change Econ Dyn 17:329–378
Winston C, Langer A (2006) The effect of government highway spending on road users' congestion costs. J Urban Econ 60:463–483