

Housing, travel, and energy spatial-temporal simulation of Riyadh: Impacts of the New Murabba Project

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Abstract: The city of Riyadh in Saudi Arabia envisions rapid growth, from a 2020 population of 7.2 million to one reaching 15 million or more by 2030 (Alhefnawi et al., 2024). A spatial economic and transport model has been developed following well-established approaches to assist in forecasting the expansion of the city, particularly the spatial organization of the population, people's housing, economic activity and employment consumption, and the flows of goods and services on the transportation network. The model, called the Riyadh PECAS model, was used to analyze the housing, travel, energy consumption, and related spatial impacts of a proposed megaproject, the New Murabba, consisting of 104,000 residences, 9,000 hotel rooms, and 4.8 million square meters of other non-residential space, anchored by a 400-meter cube-shaped megastructure with partially open interior space. The model simulates shifts in housing location, housing dwelling type, travel mode choice, travel distance, and energy use (residential and transportation). It predicts some of the details of housing consumption and location choices of Saudis and non-Saudis that provide additional insight. The non-central location of the new development could increase the total quantity of vehicle distance travelled by 6% when compared to a reference simulation where development locations are market-driven. Complementary investment in major public transit infrastructure could lead to a higher mode-split to transit and a corresponding reduction in transportation energy use. Further analysis of the New Murabba and other growth and policy options using the model could help guide Riyadh's growth.

Keywords: Spatial economic models, PECAS, land use and transport interaction (LUTI), Megaprojects, New Murabba

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1 Introduction

Riyadh is growing at an annual rate of over 4%, which is about double the national average of 2.1% and one of the fastest among large cities in the Middle East (United

Nations, 2019). It is envisioned that the population will grow from 7.2 million in 2020 to 15 million or more by 2030. This high rate has led to concerns about the carrying capacities of infrastructure and the levels of energy consumption in buildings and on the transport system in Riyadh just a few years into the future (Aldalbahi & Walker, 2016; Mikayilov & Alyamani, 2023).

The Kingdom of Saudi Arabia has placed a strong emphasis on achieving greater efficiencies in energy use. The costs of fossil fuel extraction are low, but government analysis of future economic activity is based on World Market prices for the opportunity costs of these fuels. Retail energy prices – and on electricity and gasoline for households in particular – have been increased recently (Arab Petroleum Investments Corporation, 2018). The focus on these components of energy use, along with concerns about other related aspects of sustainability, garner substantial attention in the current planning of Riyadh (Alshuwaikhat & Mohammed, 2017).

To provide planners and decision-makers with an analysis tool for considering the pace and magnitude of the approaching challenges and how to address them, we designed and built a time-series spatial economic simulation model of Riyadh using the PECAS Framework (Hunt & Abraham, 2005). It has been used to explore a range of alternative future scenarios and policy options.

This paper reports on the model, and one such application. We investigated the impacts of a proposed megaproject development called “The New Murabba” (Saudi Press Agency, 2023). It is proposed to build 104,000 housing units along with non-residential space of various kinds on approximately 19 km² of land some 20 km northwest of the current center over the period from 2023 to 2030. An important element of The New Murabba is The Mukaab, a proposed 400m by 400m mixed-use structure in the shape of a cube (400m tall), that is the showcase of the development.

We used the model to address questions and concerns about the impacts of this large addition and its design on Riyadh and its envisioned growth, and to consider some potential responses or re-alignments in planning. Our focus was the shifts in the vectors of growth in population and employment, in travel patterns and use of residential space by type, and in the corresponding changes in energy use by households for activities at home (electricity) and in travel (gasoline).

2 Spatial land use modeling and PECAS

PECAS (Hunt & Abraham, 2005) is a general theoretical framework and software platform for simulating the behavior and evolution of urban and regional areas. The framework has evolved from a line of research into “land use models,” also known as “land use transport interaction models.” The evolution of these models from early mathematical formulations of best-use allocation, (e.g., Von Thünen, 1826) into bid-rent frameworks (Alonso, 2013), (Muth, 1968) and to computer simulations has been well documented in reviews, such as (Zhong et al., 2022), (Acheampong & Silva, 2015), and (Moeckel et al., 2018). The PECAS model builds on the MEPLAN and TRANUS systems (Hunt & Simmonds, 1993), with a stronger connection to random utility theory (Abraham, 1998) (Abraham & Hunt, 2007) and a stronger separation between short-term economic equilibrium and longer term land development, operationalized in high performance operating-system independent software.

The PECAS theoretical framework unites input-output analysis (Leontief, 1986) (Hunt et al., 2005), social accounting matrices (Hunt et al., 2006), industrial location theory (Webber, 1909), bid-rent analysis, and real-estate theory (DiPasquale & Wheaton, 1996) together with random utility theory (McFadden, 1978) (Ben-Akiva & Lerman, 1985) in a holistic and consistent manner, covering choices about location, interaction,

technology, and building and infrastructure development. A typical PECAS model design starts by incorporating all the financial flows and transactions in the region from the input-output foundation and is thus a complete representation of priced transactions in the spatial economy. From this holistic foundation, the design and implementation of a particular PECAS model depends on analysis priorities and data availability. This complete and consistent foundation is suitable for investigations of secondary, cumulative, and overall impacts. A model of the entire spatial economy through time can also serve as a baseline foundation tool for further and more detailed analysis into any particular factor or element of regional growth and evolution.

Models following this type of approach have been used to assess the impacts of potential planning actions, including new infrastructure and/or policies, such as building and/or prioritizing new metro lines (Fuenmayor et al., 2018), changing transit fares (Fuenmayor et al., 2017), changing land development (De Silva et al., 2014), subsidizing types of housing (Fuenmayor & Geraldine, 2016), taxing energy use, evaluating bridge construction options (Weidner et al., 2005), and in freight-route planning (Hunt et al., 2011). The simulation traces how these potential actions are expected to impact the evolution of real-world conditions into the future, using an inter-connected representation (Abraham et al., 2013).

Planners, engineers, economists, and decision-makers can use such a model as a tool for assessing potential policy actions and developing ideas and develop multi-faceted plans that more effectively and efficiently shape their city or region (Hunt et al., 2011) (De Silva et al., 2014). Quantitative model outputs can help inform decision-making when conflicting objectives must be balanced given limited resources.

For space reasons, we cannot repeat the mathematical formulation and specification of the PECAS framework here. Interested readers should refer to (Hunt & Abraham, 2005), (Abraham & Hunt, 2007), and (Hunt et al., 2007).

Land use and transport interaction models have generalizations and assumptions. (Acheampong & Silva, 2015) summarize the field, describing the large set of approaches, theories, assumptions, and foundations. PECAS is a minimum assumption model, based on a combination of essential economic and behavioral theories. For our purposes this is seen as an advantage, allowing a comprehensive and detailed model without conceptual complexity. Within the spatial interaction component, the main mechanism is simply that activities choose locations, inputs and outputs (termed “technology”), and spatial exchange partners to trade off travel against costs, amenities, and opportunities, with each agent having unique preferences and/or perceptions (Abraham & Hunt, 2007). Within the development component, the mechanism is simply that land developers prefer to improve land where they can make a profit, based on emergent prices compared to costs, and subject to regulations (Hunt et al., 2007). This generalization is seen as a strength, not a weakness, since within this general framework a specific implementation of a model is designed around the available data, findings from data analysis, and the model’s purpose and anticipated use.

3 The Riyadh PECAS model

The Riyadh PECAS model encompasses the entire city of Riyadh, capturing interactions between households, businesses, labor flows, and spatial dynamics. The model is structured to represent economic activities, land use, and transportation systems, providing insights into urban development and policy impacts.

The model categorizes activities into three main groups:

- 1- Households: Representing residents categorized by nationality.

- 2- Industries: Covering various economic sectors contributing to Riyadh's economy.
- 3- Government and Institutions: Encompassing government activities, nonprofit organizations, and investment entities.

The Households activity is classified into two primary categories based on the nationality of the head of the household, as per Saudi Census data, Saudi and non-Saudi. This nationality separation was chosen due to its prevalence in data sources and the substantial observed difference in patterns of behavior, production, and consumption between the nationality groups. While many PECAS models use income and/or household size as key segmentation criteria, limitations in secondary data availability made nationality the most viable initial classification.

The model captures household choices related to residential dwelling type and energy consumption, particularly electricity use. This allows for an analysis of housing preferences and the associated energy demand of Saudi and non-Saudi households, supporting urban planning and infrastructure policy decisions.

The Riyadh PECAS model, like most PECAS models, is also designed with a focus on the connection between businesses and households, through labor and commuting patterns, and the trade-off between the location and use of buildings and the travel between them, for commuting trips and all other types of trips and shipments. Post-secondary education and government activities are important in Riyadh and are well represented in the Riyadh PECAS model.

The activity categories used in the model, their size in 2020, and their units of measurement, are shown in Table 1. These activities locate in zones, choose technology, and interact with each other through spatial flows. The categorization system for activities is one of the elements of the design of the model, feeding into a design diagram which is a large tableau of the model's structure. Due to its extensive nature, this diagram exceeds the constraints of a standard academic journal format and is therefore not included within this document.

Table 1. Categories of Activities in the PECAS Riyadh Model

Activity Type	Activity Name	Unit of Measurement	Quantity in 2020
Industries	AI01Agriculture	2016 SAR	3,877,953,725
Industries	AI02OilAndGas	2016 SAR	42,801,209,463
Industries	AI03Mining	2016 SAR	3,264,914,579
Industries	AI04Manufacturing	2016 SAR	54,235,054,297
Industries	AI05PetroleumRefining	2016 SAR	13,621,997,209
Industries	AI06EnergyDelivery	2016 SAR	11,657,393,838
Industries	AI07Water	2016 SAR	5,574,013,434
Industries	AI08ResConstruction	2016 SAR	11,430,278,724
Industries	AI09NonResConstruction	2016 SAR	23,799,431,956
Industries	AI10WholesaleRetailAndAccommodation	2016 SAR	194,000,000,000
Industries	AI11Transportation	2016 SAR	51,836,716,737
Industries	AI12Information	2016 SAR	68,398,083,156
Industries	AI13FinancialAndBusiness	2016 SAR	144,000,000,000
Industries	AI14RealEstate	2016 SAR	58,427,732,239
Industries	AI15PublicAdmin	2016 SAR	57,135,715,806
Industries	AI16Education	2016 SAR	41,367,264,910
Industries	AI17Health	2016 SAR	18,299,456,158
Industries	AI18ArtsAndRec	2016 SAR	5,748,154,767
Industries	AI19OtherService	2016 SAR	11,191,845,824
Institutions	AA40NonProfit	2016 SAR	133,079,310
Government	AA41GovtSpend	2016 SAR	6,276,922,624
Institutions	AA42Investors	2016 SAR	101,000,000,000
Households	AH60Saudi	Households	693,148
Households	AH70NonSaudi	Households	430,373

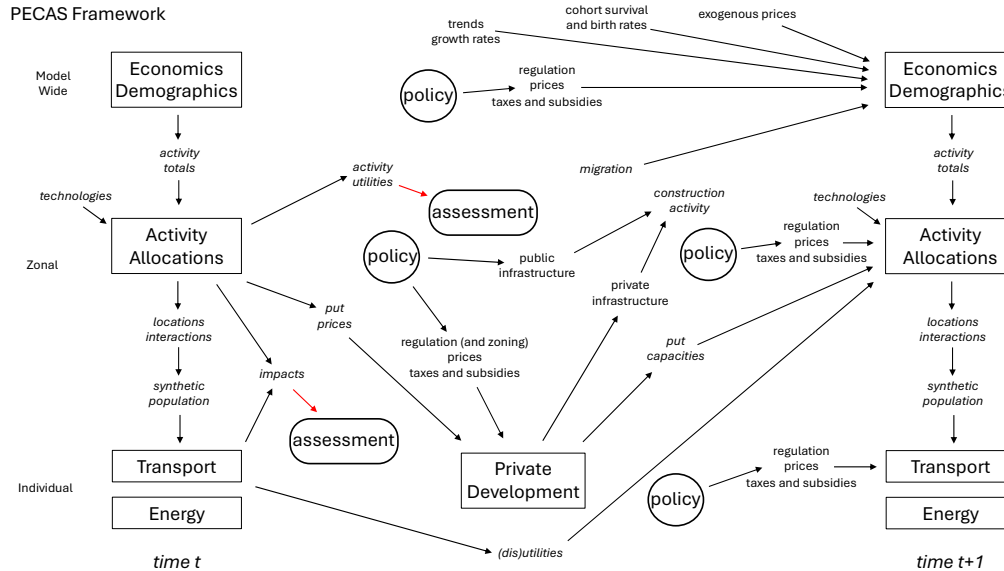


Figure 1. Flow chart of the Riyadh PECAS model

Source: Authors

Figure 1 shows the information flows in the Riyadh PECAS model as it evolves its representation of Riyadh from year to year. The Economics and Demographics system forecasts the activity totals in each year, for example, the numerical values in Table 1 for 2020. These are allocated to locations, and technologies, with resulting flows, in a short-term spatial price equilibrium for all interaction types (“put prices”) each year. These interactions drive the representation of transport and transport energy. The prices for real estate that emerge drive the simulation of Private Development on parcels between years, allowing the next year’s simulation to progress, with updated activity totals, capacities of real estate (building inventory), and updated travel conditions ((dis)utilities). Policies can be adjusted to set up different scenarios, while assessments can be calculated from the model’s outputs.

The reference scenario for the PECAS Riyadh model (a business-as-usual scenario without the New Murabba project described below) was developed using economic, land parcel, household, labor force, real estate, business, and transport data. A large variety of sources were employed, with interactions, choices, and measures of quantity incorporated into the model, always reconciling against the high-level economic view. This involved aggregating or disaggregating as necessary to fit into the model’s design, and associated data cleaning and updating. The most important data sources include:

- Households Survey for Ar-Riyadh Development Authority (Royal Commission for Riyadh City (RCRC), 2016a),
- Labor force and household expenditure data (General Authority for Statistics, 2019),
- The Input-Output table for Saudi Arabia (King Abdullah Petroleum Studies and Research Center, 2016),
- Land use parcel data (Royal Commission for Riyadh City, 2016b),
- Land use zoning plans (High Commission for the Development of Arriyadh, 2021) and visions (Arriyadh Development Authority, 2013),

- Transport conditions and network from RCRC travel model (IBI Group, 2005).

The base year of the model is 2016, and the simulation period runs from 2016 to 2050. The model simulates the behavior of the households in Riyadh (about 1 million in 2016, more than doubling by 2050) and industry activity (including government offices and education facilities), forecasting their locations, choices of residential dwellings by type and size, use of non-residential space, residential electricity demand, and labor market choices, among other outputs. The calibration of the model provides for different behaviors and elastic response, including:

- Trip length and flow distance: each of the spatial connections represented, including labor flows (commuting), goods, and services, were calibrated to observed trip length distances, to represent the spatial choice of traveling further to interact with a more suitable activity (e.g. the chosen school, employer, or supplier), as a trade-off between suitability (as represented by the random term in random utility theory (McFadden, 1978)), travel costs, and emergent short-term equilibrium prices. (Abraham et al., 2008)
- Location choice: the allocation of different household types and different industrial categories to zones was calibrated with the floorspace rent observations (Saudi Riyal, SAR, per square meter per year), to represent the higher prices emergent in more desirable locations after accounting for travel costs.
- Floorspace construction: the Space Development module in PECAS is a deterministic parcel based microsimulation of construction, it was calibrated using a Bayesian search process (Hill, 2017) to represent the construction industry's response to land availability (regulated by policy, e.g. zoning), rents, and construction costs.
- Floorspace use: elasticity of space use is essential for a real estate market model, so that higher demand can lead to higher prices which stimulate supply. For non-residential space, this was calibrated to limited data on industrial location and non-residential space use, along with non-residential rents. For residential space, this is described in the next section, below.

4 Representation of housing and domestic electricity demand

The Riyadh PECAS model is meant to be a continuously evolving simulation, considering new data as it becomes available, and adding (or subtracting) features or detail depending on policies or issues that are important in any particular year. At this moment in time, one of the important elements of the Riyadh PECAS model is the representation of housing (residential dwelling) and energy demand.

The top level of the additive logit model in the PECAS Activity Allocation model is location choice, while the bottom level is spatial interaction choice. In between, in the middle level, is a discrete choice of technology, being the rates of consumption of inputs and the rates of production of outputs for the different activity categories (Abraham & Hunt, 2007). For household activity categories this represents a lifestyle choice, but in this paper we use the generic term "technology choice." Since the model is a discrete choice model, the representation of continuous variables, such as size of dwelling, or quantity of electricity purchased, is not explicit. Rather, we represent certain endpoints,

letting the logit model blend them together in appropriate proportions to achieve the desired average use rate and elastic response to prices or accessibility.

The Households Survey for Ar-Riyadh Development Authority (Royal Commission for Riyadh City, 2016a) contains information on the household and its dwelling. Dwellings are represented by five categories: Villas, Apartments, Traditional Arab House, and Other Residential (usually living quarters in commercial establishments). Townhouses are a sixth category, but they are functionally similar to smaller villas so were combined in the choice model. The use rates of different types of dwelling by Saudi and non-Saudi households are shown in Table 2.

The table shows the difference in residential use patterns between the nationality groups. In particular, Saudi households are more likely to use villas and traditional Arab houses, and their homes tend to be larger in size, whereas non-Saudis are in smaller homes and most likely to be in apartments. This difference in behavior justifies the separation of the population into these groups in the model.

The technology options for the technology choice model were initially set up with 15 discrete options for each nationality group: the five dwelling types each with three dwelling sizes. The small dwelling option was based on the 15th percentile observations, the large option on the 85th percentile observation, and the average dwelling option based on the mean of the observations.

Table 2. Count of Households by type and housing type

Source: Statistical metrics of housing size by type and nationality calculated using synthesized households for Riyadh, which employed household data from the RCRC Household Survey as sample, and Census data as targets

Household Type	Housing Type	Count of Households for 2016	Std. Dev. Size (m ²)	Ave Size (m ²)	Min Size (m ²)	Max Size (m ²)	15 th Size (m ²)	85 th Size (m ²)
Saudi Households	Villa	391,266	171.55	334.10	14	990	200	500
	Palace	618	275.32	742.56	150	950	220	900
	Apartment	201,037	104.73	146.97	24	951	80	220
	Traditional House	45,197	201.69	249.66	22	900	56	500
	Other Residential	1,624	234.61	266.92	16	900	40	660
Non-Saudi Households	Villa	43,188	120.43	169.46	12	990	60	300
	Palace	75	189.83	766.67	500	900	500	900
	Apartment	315,165	95.91	112.98	10	901	50	150
	Traditional House	20,717	69.45	137.05	20	780	80	200
	Other Residential	14,796	171.43	126.27	10	950	20	200

The model's response of average dwelling size in a *hai* (neighborhood, there are 163 zones in the housing demand model most corresponding to a single *hai*) for the different dwelling types and nationalities to rent changes were investigated, and parameters were further adjusted to match the observed behaviour in the Household Survey. During this adjustment process, the region-wide mean dwelling size was maintained, while the small dwelling size and large dwelling size, and the logit model dispersion parameters were

adjusted. Figure 2 shows some of the dwelling size resulting response curves for Saudi households. The calibrated housing demand model shows significant price elasticity on dwelling size for villas and palaces.

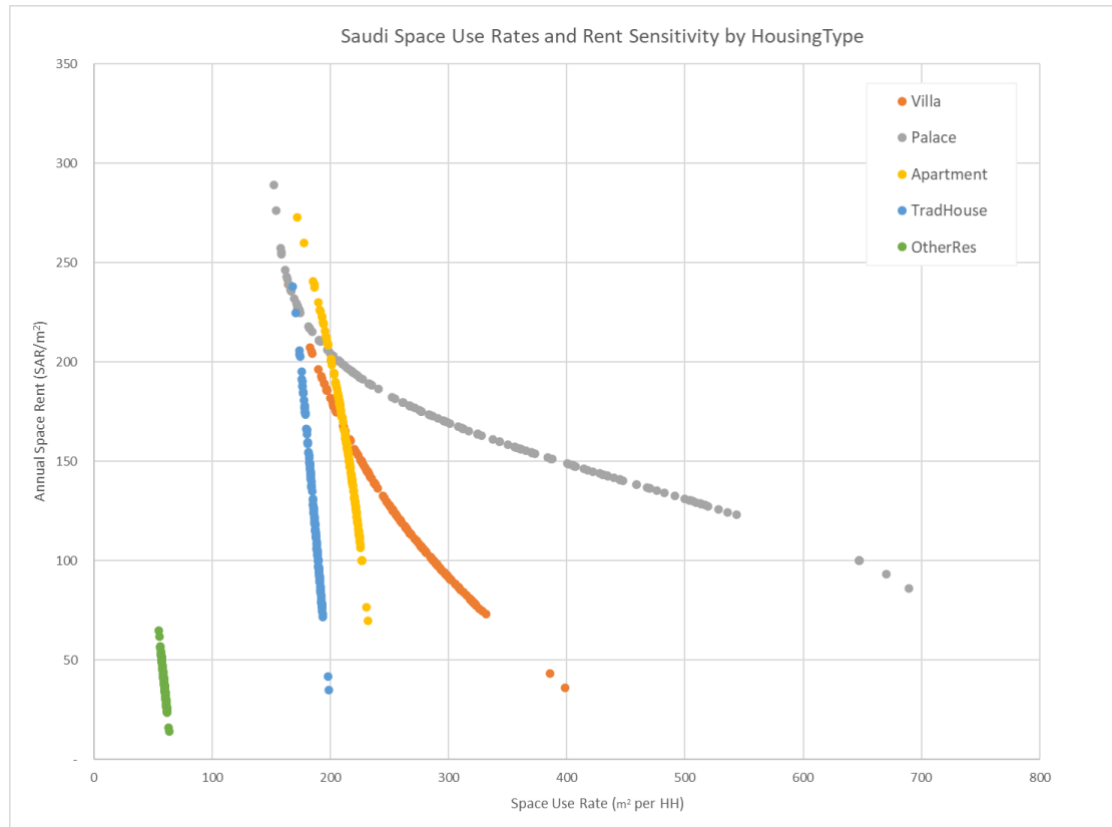


Figure 2. Dwelling size response to price for Saudi households in one land use zone

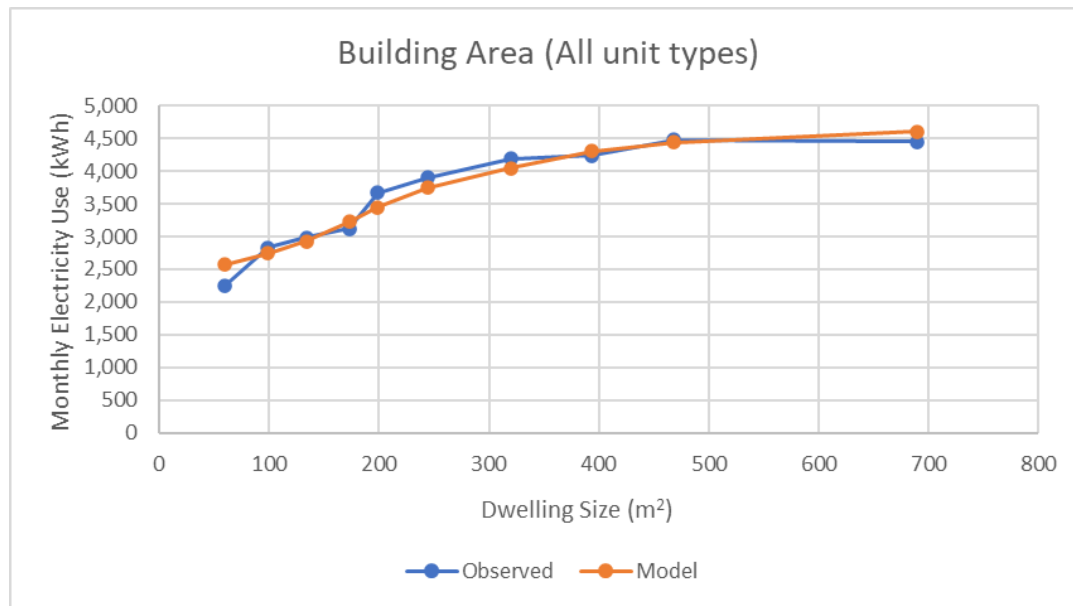
The households' expenditure on domestic electricity is available for a subsample of 2,706 of the 13,965 households in the RCRC Households Survey. These data were analyzed using multiple linear regression. The dependent variable was the reported monthly expenditure on electricity, converted into monthly kWh of electricity consumption using the prices for domestic electricity in 2016. After dropping 115 records with expenses of zero, and 18 records with expenses over 2000 SAR (10 times the median expenditure), 2573 records were used for estimation.

The parameters of the selected energy use model incorporated into the PECAS Riyadh model are shown in Table 3. The R-squared of the estimation is 0.295.

Table 3. Selected energy use model by housing type incorporated into the PECAS Riyadh model, in annual kWh

Parameter	Coefficient	Standard Error	T Ratio
Constant allocated to all units	2045.4163	60.934	33.568
Area of dwelling if indigenous Arab house, in square meters	2.028	0.39	5.2
Area of dwelling if villa or palace (Single family dwellings)	1.6364	0.235	6.949
Area of dwelling if townhouse, or “other” which is most often a dwelling in a shared commercial space, but also consists of miscellaneous arrangements	1.4749	1.438	1.025
Area of dwelling if apartment	0.9132	0.349	2.617
Additional constant for indigenous Arab house	357.4621	97.529	3.665
Additional constant for villa or palace	800.5605	116.605	6.866
Additional constant for townhouses and miscellaneous dwelling types	624.9756	199.201	3.137
Additional constant for apartments	262.4182	88.065	2.98
Additional amount for Saudi households in indigenous Arab house	524.5316	119.647	4.384
Additional amount for Saudi households in a villa or palace	1048.7791	126.991	8.259
Additional amount for Saudi households in townhouses or miscellaneous dwelling types	480.9034	423.796	1.135
Additional amount for Saudi households in apartments	821.4715	122.371	6.713

The model is sensitive to the size and type of the dwelling, as shown in Figure 3 and Figure 4. These figures show the results of applying the model to each sample, comparing the mean observed and mean modelled values for different categories of dwelling size band and dwelling type. Although there is significant variation in the individual observation of energy use, as seen in the 0.295 R^2 value, the figures show that average value of groups of households is well predicted.

**Figure 3.** Monthly mean electricity use by dwelling size for all types of housing (observed vs modelled)

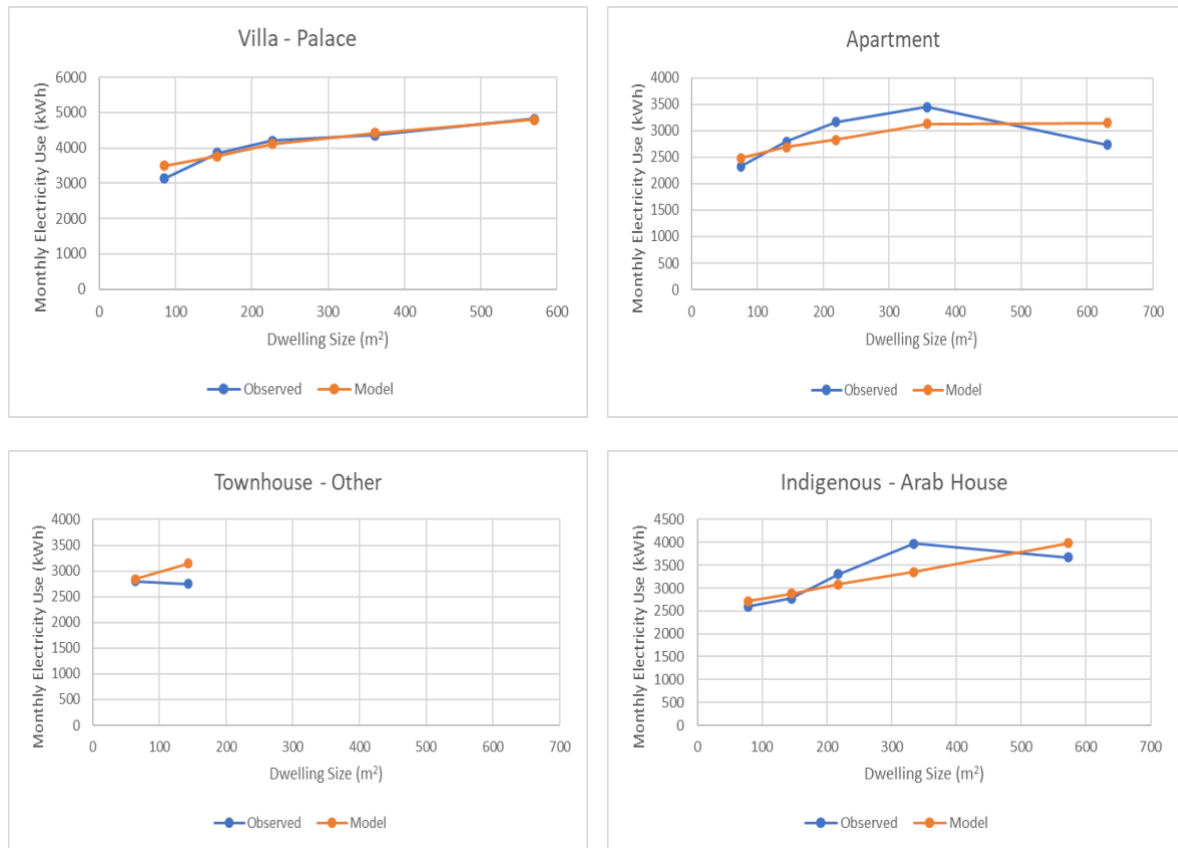


Figure 4. Monthly mean electricity use by dwelling size and housing type (observed vs modelled)

To incorporate elasticity demand into the technology choice representation, each of the fifteen housing options was further split into two electricity consumption options, a higher electricity consumption option, and a lower electricity consumption option, with electricity consumption in between these variants represented as a choice-model blend of the two more extreme options. The sensitivity in choosing between options, the level of the higher and lower electricity variants, and the a-priori likelihood of choosing one variant (vs the other) were calibrated to reproduce the modelled rates, and to achieve a model-wide all-resident price elasticity of -0.57 , consistent with the range reported in (Mikayilov, Fakhri, et al., 2020) as cited in (Mikayilov, Darandary, et al., 2020).

In PECAS all price and cost variables are internally consistent as annual money cost, a feature that enables consistency and ease when comparing policies across different domains. The electricity use rate has a higher percentage response to annual household cost than the dwelling size and type choice response. Wide ranges in the two endpoints of electricity consumption were needed to represent this, since the choice model is simultaneous in both housing and electricity and is a multinomial logit formulation. The high electricity rate option was set to 500% of the mean, and the low electricity rate option was set to 20% of the mean. The model's alternative specific constants for the two options were calibrated so that in 2016 the mean electricity consumption for each housing option matches the estimated values, thus the model respects both the observed consumption and the observed price response.

The dwelling and electricity use rates for the resulting technology options are shown in Table 4.

Table 4. Dwelling and electricity use coefficients by household and housing type in the PECAS Riyadh Model's Technology Options. Continuous response is simulated by blending these discrete options in response to prices, availability, and other considerations.

Household Type	Housing Type	Small Dwelling (m ²)	Average Dwelling (m ²)	Large Dwelling (m ²)			
Saudi	Villa	60	230	560			
	Palace	150	770	8,755			
	Apartment	50	147	250			
	Traditional House	60	275	179			
	Other Residential	1	50	121			
Non-Saudi	Villa	60	177	482			
	Palace	150	770	6,681			
	Apartment	50	113	258			
	Traditional House	60	210	511			
	Other Residential	1	50	107			
Household Type	Housing Type	Small Dwelling Electricity Use		Average Dwelling Electricity Use		Large Dwelling Electricity Use	
		Minimum (kWh)	Maximum (kWh)	Minimum (kWh)	Maximum (kWh)	Minimum (kWh)	Maximum (kWh)
Saudi	Villa	9,406	235,158	10,251	256,268	11,547	288,668
	Palace	9,937	248,413	12,371	309,287	43,730	1,093,254
	Apartment	7,563	189,073	7,833	195,813	8,058	201,462
	Traditional House	7,133	178,322	8,364	209,107	7,897	197,435
	Other Residential	7,567	189,166	7,740	193,502	7,990	199,744
Non-Saudi	Villa	6,889	172,231	7,525	188,137	8,834	220,848
	Palace	7,419	185,486	9,854	246,360	33,068	826,710
	Apartment	5,561	139,018	5,786	144,662	6,398	159,941
	Traditional House	5,864	146,606	6,789	169,726	12,649	316,223
	Other Residential	6,412	160,312	6,586	164,648	6,787	169,676

5 The New Murabba megaproject

The New Murabba is a large proposed development in Riyadh, as part of Vision 2030 which aims to transform the Kingdom of Saudi Arabia and its cities (Abdallah, 2021). It would be funded by the Saudi Public Investment Fund (PIF), which targets to unlock the

capabilities of promising strategic sectors in the Kingdom, contribute to the development of real estate projects and the local infrastructure, and diversify the Saudi economy's sources of income (Saudi Press Agency, 2023).

The Public Investment Fund (PIF) of Saudi Arabia has initiated multiple transformative Kingdom-wide projects, such as NEOM, a futuristic new city on the northwest coast of the Kingdom of Saudi Arabia (KSA), which promotes a new way of sustainable living in the future; and Red Sea Global which is planned as a new destination in the west coast of the Kingdom to boost tourism in the country.

Riyadh is one of the fastest growing cities in Saudi Arabia (United Nations, 2019) and is expected to be at the center of the country's visionary transformation. The New Murabba is the most recent proposal to redefine the future of Riyadh as part of the vision planned for the Kingdom (Saudi Press Agency, 2023).

6 Proposed development

The location of the New Murabba development is proposed north of King Salman Road, spanning an area of 19 Km², approximately 20 Km south-west of King Khalid International Airport. This new development is expected to be situated between Al-Qairawan and AlDiriyah districts. The potential boundary of the development is illustrated in Figure 5. The expected year of completion for the project is 2030 (Public Investment Fund, n.d.).

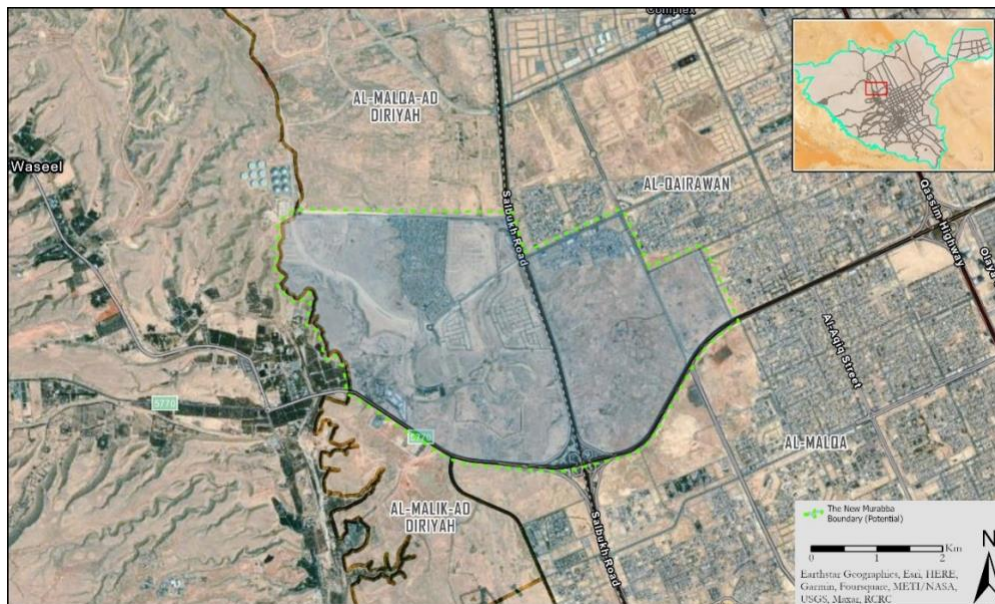


Figure 5. Location of the New Murabba project development

According to the official announcement, the New Murabba development will encompass various land-use types, including residential, retail, office, and public spaces. The type of space and expected quantities in the development plan are summarized in Table 5.

Table 5. Floor space types and quantities that were included in the official announcement of the New Murabba development

Source: SPA (2023)

Floor space type	Quantity	Unit
Residential	104,000	Unit
Hotel	9,000	Room
Retail	980,000	m ²
Office	1.4	Million m ²
Public	1.8	Million m ²
Leisure	620,000	m ²



Figure 6. The Mukaab

Source: newmurabba.com

Much of the media attention for the New Murabba development focuses on the Mukaab, a cube with a width and height of 400 m high, a structure envisaged to be “bigger than 20 Empire State Buildings,” the “world’s first immersive, experiential destination,” featuring 2 million m² of floor space that will be a premium hospitality destination with a multitude of retail and touristic attractions, along with residential and hotel units, commercial spaces, and recreational facilities (SPA 2023). But most of the envisioned development for the New Murabba (Table 5) will be outside of the Mukaab.

7 Simulating the New Murabba project

We developed a scenario in the Riyadh PECAS model representing the development of the New Murabba by entering the construction amount of residential and non-residential space from year 2024 to 2029. These construction amounts were estimated from the space types and quantities announced in Table 5.

We suppose the total amount of space construction of 6 distinct space types to be 26 million m², on a total of 14.3 million m² of land, as shown in Table 6. This is an additional amount of development which, in this scenario, we ask the model to build during the simulation, in specific locations and years as described below. The estimated land area used represents 75% of the 19 km² allocated project area, allowing 25% of land for non-building use, such as transportation and utilities right of ways.

Table 6. Scenario inputs representing the size of New Murabba development, including the Mukaab, by year

Source: Authors' analysis based on estimated construction amounts and construction density assumptions based on the New Murabba description in Table 5.

	Commercial / Retail	Office	Mixed Use Apartment	Apartment	Townhouse	Villa	Grand Total
Year	Square Meters of Space						
2024	284,682				480,008		764,690
2025	1,290,080				1,511,480		2,801,560
2026		192,720	408,059		1,903,657		2,504,436
2027	850,318	1,014,876	4,182,585	1,538,506	961,511		8,547,795
2028	1,035,377		2,175,718			2,463,785	5,674,880
2029	540,290		2,890,071			2,366,920	5,797,281
Total	4,000,747	1,207,596	9,656,433	1,538,506	4,856,656	4,830,705	26,090,642
Year	Square Meters of Land						
2024	71,158				282,308		353,466
2025	322,462				888,949		1,211,411
2026		110,739	119,994		1,119,599		1,350,333
2027	34,007	40,588	1,229,942	61,529	565,493		1,931,559
2028	230,039		639,795			3,909,988	4,779,822
2029	120,041		849,857			3,756,236	4,726,134
Total	777,707	151,327	2,839,588	61,529	2,856,349	7,666,224	14,352,725

Our sequencing is based on assumption and expert judgement. We assumed that the largest quantity of space, and the Mukaab itself would be completed in 2027; this is reflected in the schedule of construction in large amounts of Apartment, Commercial/Retail and Office Space in 2027. The schedule is also shown in Figure 7.

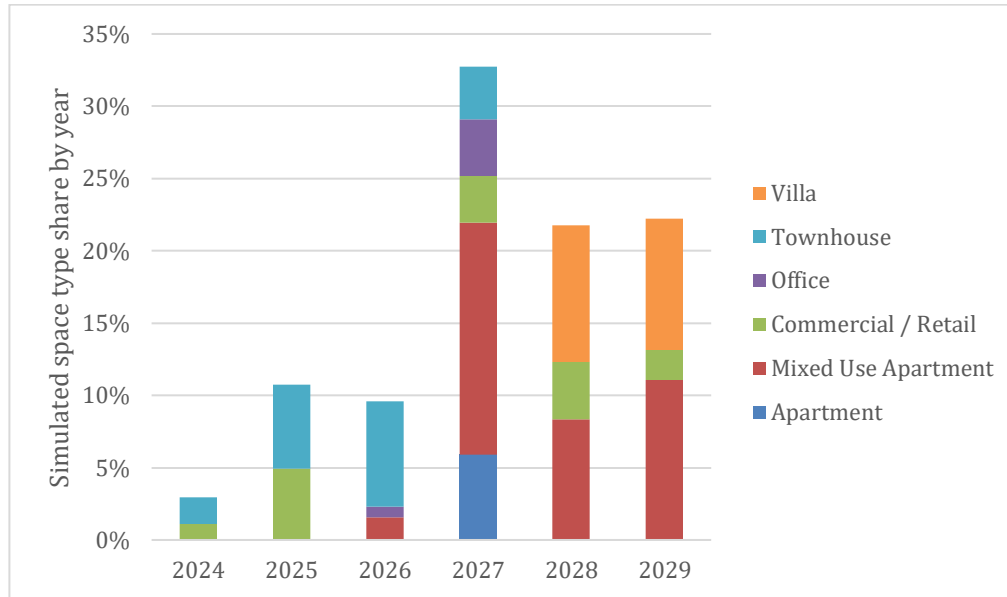


Figure 7. Share of simulated space by type, inputs in the New Murabba scenario, from 2024 to 2029

Figure 8 illustrates a detailed pattern of the project's development which was input to the simulation scenario in the model. The figure shows the transportation analysis zones (TAZs) that are affected, numbered 692, 539 and 538. TAZ 692 had large parcels which we subdivided systematically and algorithmically into smaller ones; for the most part, these parcels have been designated for Villa space type development and are simulated to be built in the years 2028 and 2029. For the other two TAZs we assigned the new development onto the pre-existing land subdivision patterns, with The Mukaab occupying pre-existing parcels at the center of TAZ 539. The detailed sub-TAZ development pattern is necessarily arbitrary since a detailed construction plan is not yet published. We inspected project presentation videos to come up with an allocation into the three TAZs, and then followed a reasonable pattern within each TAZ based on existing patterns in Riyadh. We report results aggregated to the TAZ level or higher, so this detailed spatial pattern at the sub-TAZ level has little impact on our reported results. However, both the detailed spatial pattern and the schedule sequence by year represents one particular development pattern for the project; the model could be used to investigate other detailed options as well.

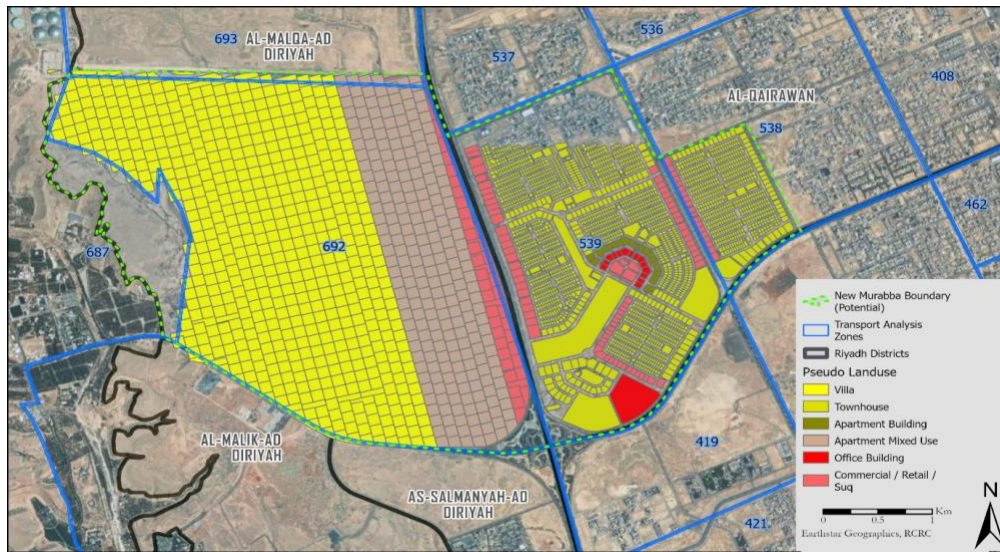


Figure 8. Simulated pattern of development for the New Murabba project by TAZ

In the New Murabba scenario, the project alters the real estate market in the designated project area. As part of the simulated response, the PECAS Riyadh model adjusts the demand of space, the supply of space in other locations (and in the New Murabba locations beyond the schedule of scenario inputs which end in 2029), and the resulting rents, providing a new resulting pattern of space development across the entire city. The two scenarios (the New Murabba and reference) were run and compared. The rate of growth of households, jobs, and the economy is identical in the two compared scenarios.

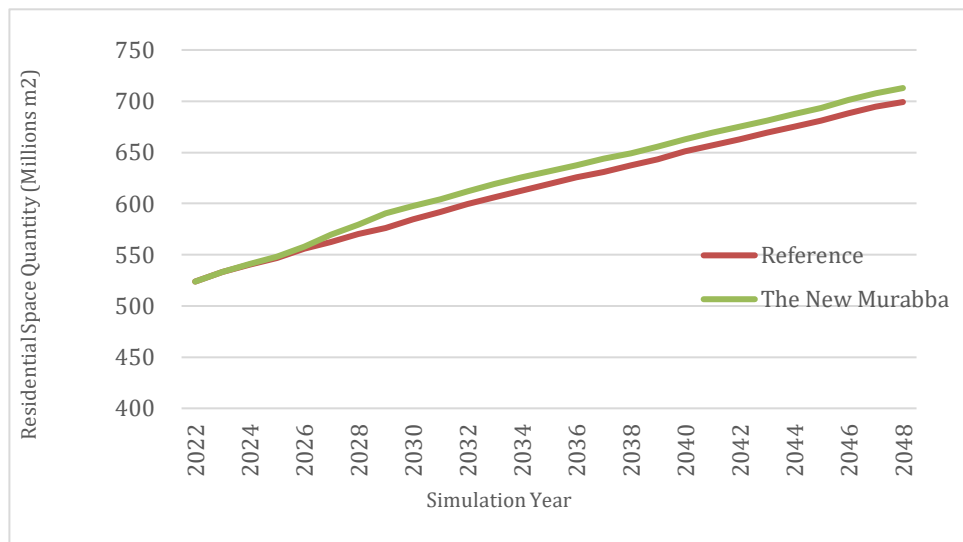
8 Spatial impacts and patterns

The New Murabba simulation allocates the households differently by dwelling type (Table 7) based on the simulated response following the household's calibrated preferences. Saudi households occupy an additional 6,500 villas in 2030, while non-Saudi households occupy around 9,000 less dwellings of this type, when compared against the reference scenario's 2030 prediction. Approximately 12,500 less Saudi households live in apartment units, while close to 15,700 more non-Saudi households live in Apartments. This full effect is due to the complex interaction of preferences and flows of goods, services, and labor in the economy, but, from our investigations it is apparent that the primary explanation for this shift is that the villas provided in The New Murabba are well-suited to Saudi lifestyles, while the apartments provided in The Mukaab and elsewhere are well-suited to non-Saudi lifestyles. As Saudi's move towards the new development, primarily to its villas, apartments elsewhere are freed-up for occupation by non-Saudis; and as non-Saudis move towards the new development, primarily to its apartments, villas elsewhere are freed-up for occupation by Saudis.

Table 7. Number of occupied residential units by type in the two scenarios in 2030

Unit Type	Reference			The New Murabba			Difference		
	Saudi	Non-Saudi	Total	Saudi	Non-Saudi	Total	Saudi	Non-Saudi	Total
Villas	592,775	129,890	722,665	599,272	120,905	720,177	6,497	-8,985	-2,488
Palace	1,332	2,675	4,007	1,339	2,075	3,414	7	-600	-593
Apartment	201,763	336,452	538,215	189,237	352,156	541,393	-12,526	15,704	3,178
Traditional House	47,121	33,570	80,691	53,351	32,576	85,927	6,230	-994	5,236
Other Residential	1,953	22,035	23,988	1,745	16,910	18,655	-208	-5,125	-5,333
Total Units	844,944	524,622	1,369,566	844,944	524,622	1,369,566	0	0	0

Figure 9 shows the total residential space in Riyadh to 2048. The New Murabba scenario has more space overall than the reference scenario, but this additional quantity is a small portion of the total growth over time. The number of households in each year is the same in each scenario, so there are more housing opportunities and larger average dwellings in the New Murabba scenario.

**Figure 9.** Annual quantity (m²) of residential space simulated for reference and the New Murabba scenarios

A comparison map of the simulated number of households is shown in Figure 10. The model simulates more than 50 thousand households moving to the New Murabba project by 2030, and this trend continues until 2050. The total number of households is the same in both scenarios, growing by 200,000 households between 2022 and 2030; the 104,000 dwellings envisioned in the New Murabba development (Table 5) can accommodate half of this anticipated growth. The growth in the total quantity of space is not impacted after

the New Murabba is completed in 2030. But the locations of the space do continue to evolve differently in the New Murabba scenario as compared to the reference scenario.

Most of the shifts are localized, shifting growth patterns from the immediate east of King Fahd Road towards the new development. Figure 10 also shows that both with and without the New Murabba project the model simulates a very large amount of development in the northeast area. This other development is still larger than The new Murabba development in the New Murabba scenario (Figure 10), but smaller (Figure 11), than in the reference scenario because of the general shift towards the west where the new project is situated.

The gray colored polygons in Figure 10 and Figure 11 show that the other TAZs and LUZs are not much affected.

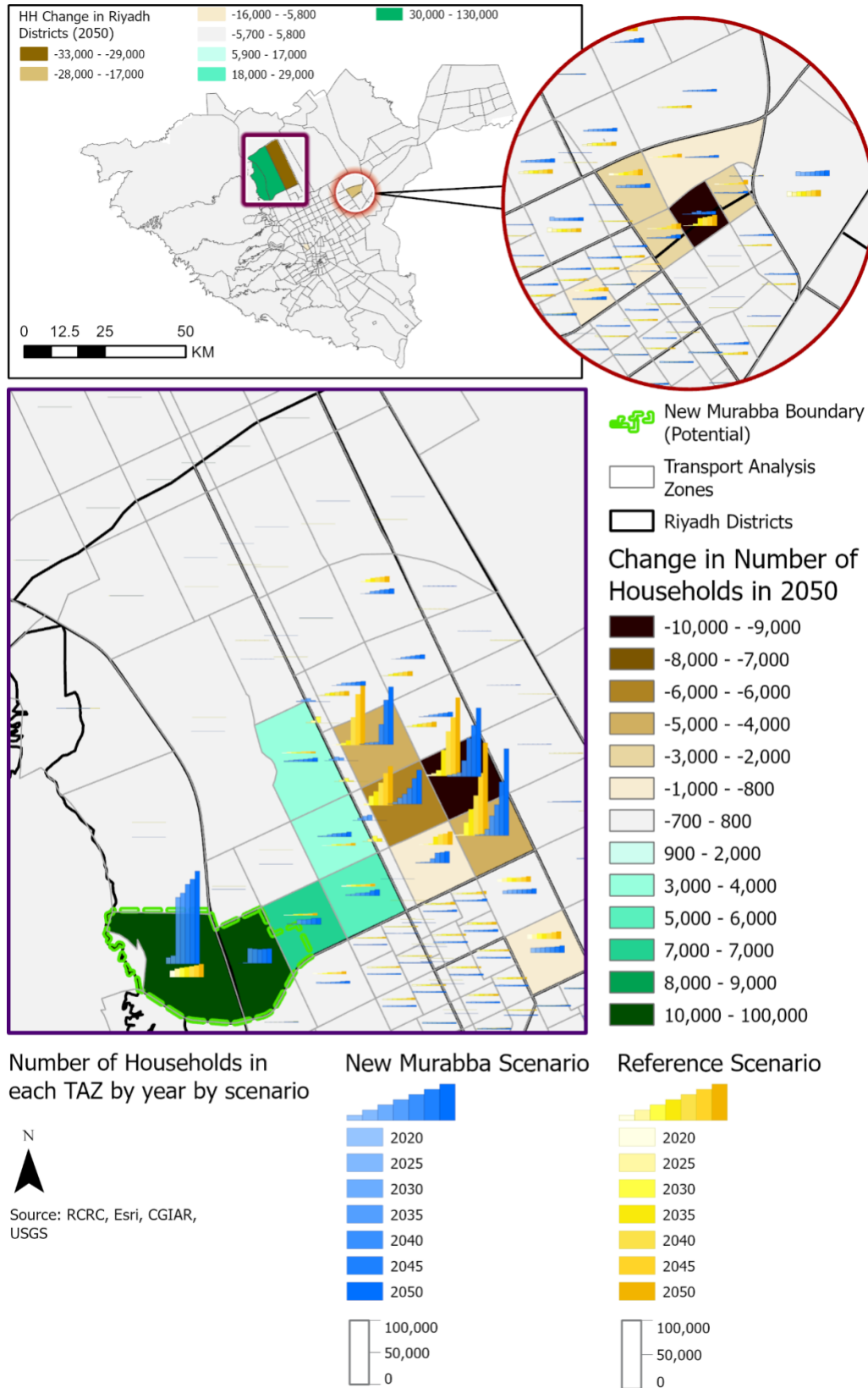


Figure 10. Total households' allocation over time after building the New Murabba project – totals of households by scenario by TAZ with difference of households by TAZ

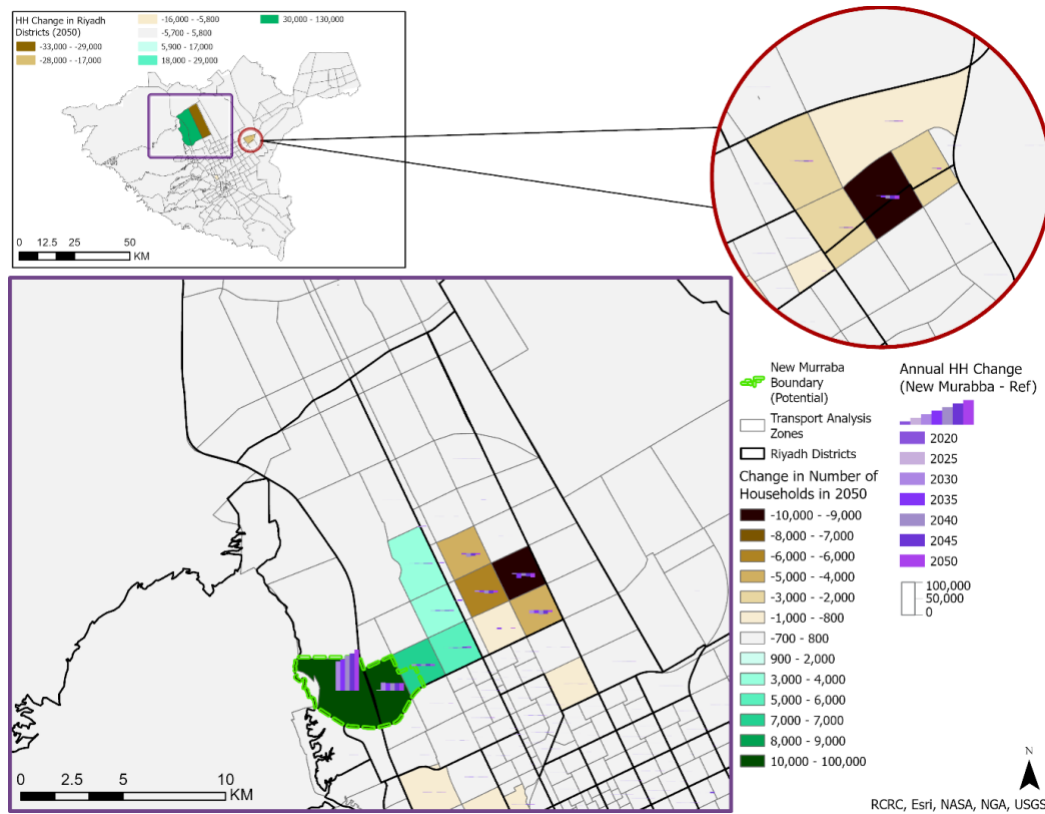


Figure 11. Change in households' allocation over time after building the New Murabba project –annual household difference by TAZ between the New Murabba and the reference scenario

Labor patterns also shift. The shifts compared to the reference scenario in the year 2050 are shown in Figure 12. Labor shifts into the New Murabba land use zones, but there is a further shift towards the west in general, reflecting the commuting opportunities of the residents in the New Murabba. Areas in the east do not grow as quickly. The brown area of Figure 12 are the neighborhoods (“hais”) of Ar-rabwah, King Abdullah and perimeter portions of King Abdulaziz forgoing some of their job growth in favor of the New Murabba development, and other areas more to the west.

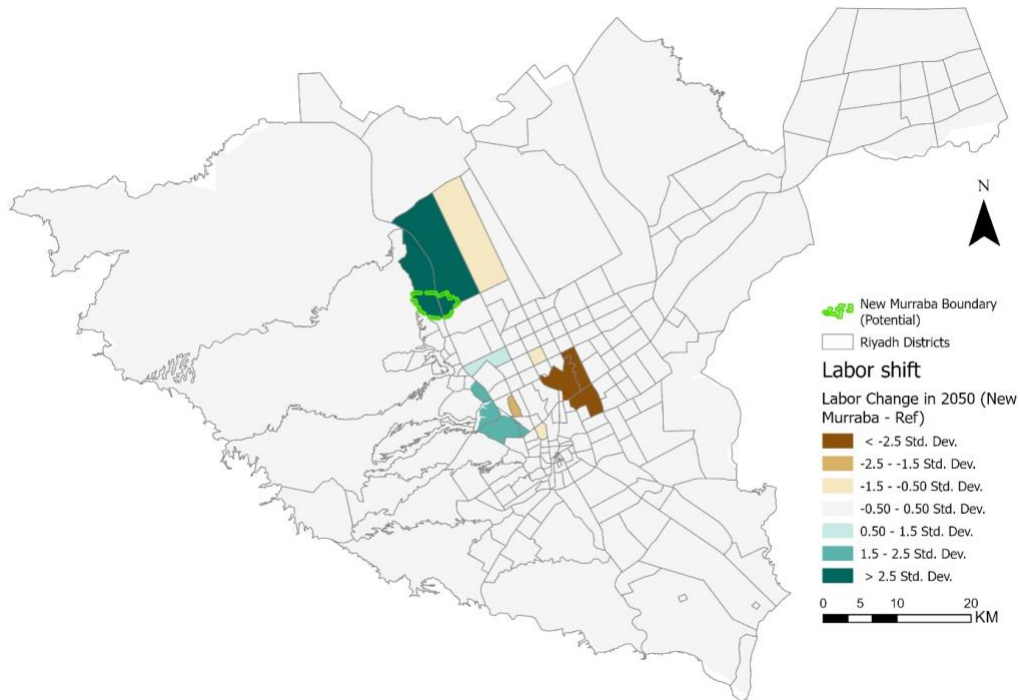


Figure 12. Change in labor use (workplaces) between the two compared scenarios for 2050

9 Household electricity use

The PECAS Riyadh model indicates that with the New Murabba project there is more household (domestic) energy use as electricity. The number of households is the same in both scenarios, but there is a shift in structure type, location, and space quantity to match the increased supply in The New Murabba project. This leads to a larger demand for domestic electricity for households, to support air conditioning and other uses. Many households tend to allocate in central north Riyadh for the year 2050 in both scenarios, but with the project some growth switches to the zone in the west (Figure 13). The model also indicates that the demand for electricity switches from the south, the east and from downtown to this new west location. Figure 14 shows the difference in annual use of electricity by household category every five years until 2050.

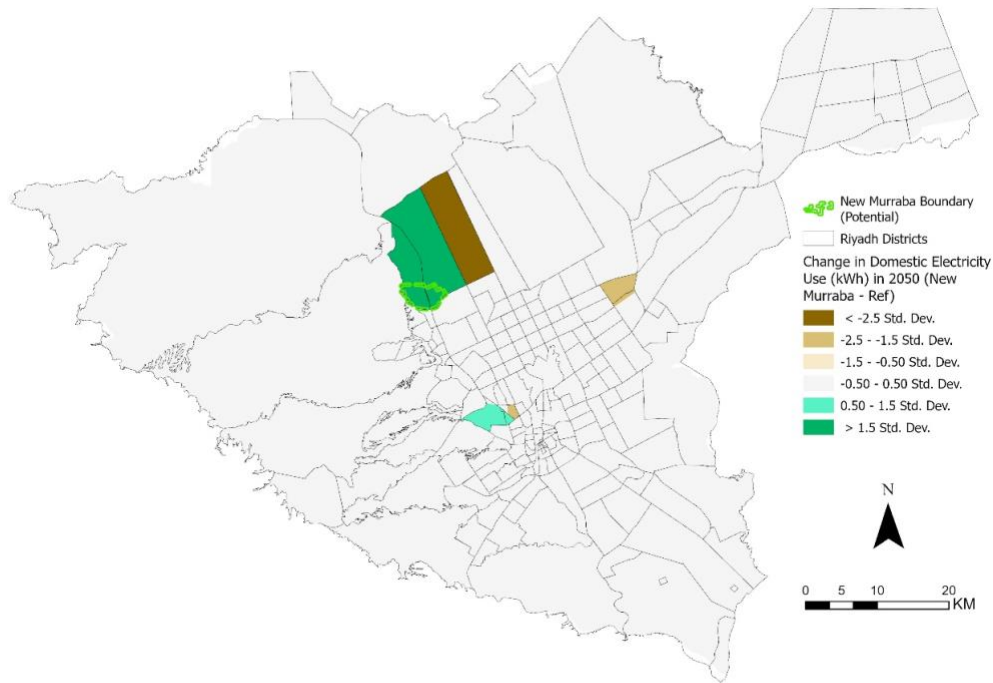


Figure 13. Change in domestic electricity use between the New Murabba project and the reference scenario in 2050

The New Murabba project provides an increase in villa space for the city, allowing residents, especially Saudi households, to enjoy larger overall dwelling sizes when choosing villas, with an associated increase in electricity use. The project also provides more energy efficient apartment opportunities that lead to reduced electricity use, these are enjoyed proportionally more by non-Saudis, leading to less energy use by non-Saudis. Both nationality groups (Saudis and non-Saudis) use all types of housing, but Saudi households, on average, benefit more from large villas, and the calibrated demand model (described in section 4) simulated Saudis choosing them with a higher probability, as shown in Table 7.

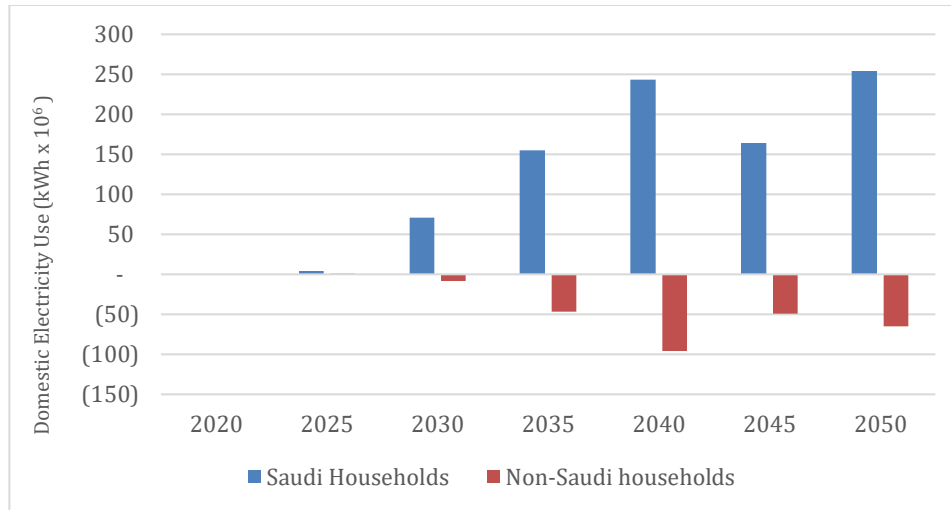


Figure 14. Change in annual domestic electricity use with the New Murabba project

10 Changes in travel patterns and resulting energy use in travel

The traffic flows and resulting congestion levels for a weekday PM peak hour for the year 2030, both with and without the New Murabba, as simulated by the RCRC travel model, are shown in Figure 15 and Figure 16. The RCRC travel model indicates that the congestion on roadways near the New Murabba project would be severe without major increases in capacity. All the model results are affected by the lack of additional capacity in the model networks.



Figure 15. Level of service on roadways without the New Murabba project (Reference scenario). Congestion is represented as volume to capacity ratio: Free Flow (0 to 0.7), Moderate (0.7 to 1) and Severe (>1)



Figure 16. Level of service on roadways with the New Murabba project. Congestion is represented as volume to capacity ratio: Free Flow (0 to 0.7), Moderate (0.7 to 1) and Severe (>1)

11 Comparing energy impacts of residential and traffic changes

With the New Murabba, the travel model simulates an increase in energy consumption in typical weekday travel of 21,400 GJ/weekday, 6% higher than without the project (Figure 17) based on current vehicle fleet fuel consumption statistics. Multiplying by 300 (to approximate a yearly aggregate total; there is less traffic on weekends) results in 6.4×10^6 GJ/Year. To compare with domestic electricity use, we convert this into kWh, multiplying by a conversion factor of 277.78 kWh/GJ. This results in a difference in energy consumed of about 1.78×10^9 kWh/year due to changes to travel patterns in the year 2030.

The model indicates that the change in travel patterns resulted in an increase of energy use that is 27 times higher than the increase in domestic energy use (Figure 14) with the New Murabba project. This is also an average amount per-household, since the two scenarios didn't differ in the number or nationality of households each year.

Overall, the New Murabba attracted substantial numbers of trips for various purposes, and given the non-central location of the development, this increased the average trip length and the associated energy use in travel. The reference scenario, with more growth close to the central axis (Figure 10), supports shorter trips lengths than the New Murabba scenario.

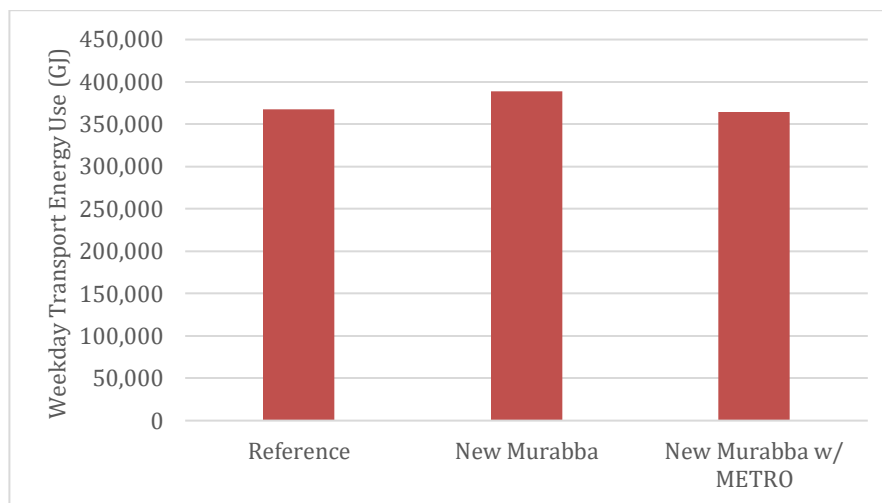


Figure 17. Annual household's weekday transport energy use for the reference, the New Murabba and the New Murabba with metro extension scenarios for 2030

12 Metro extension scenario

The RCRC travel model for the 2030 scenario that is used to inform PECAS Riyadh contains many stations but none at the location of the New Murabba (Figure 18). We developed a set of inputs for the RCRC travel model that has a Metro station at the New Murraba (Figure 19). Results indicate that providing a metro service to the New Murabba project would mitigate the potential increase in travel energy use (Figure 17 and Figure 20), and even reduce it beyond the reference scenario. In all scenarios the road networks are quite congested by 2030. The compact development of the New Murabba scenario allows the metro system to contribute to a reduction in vehicle distance travelled and hence a reduction in energy use. A substantial mode-split to metro is generated as a

behavioral response in the RCRC travel model when metro is provided; for example, over 50% of AM peak traffic leaving The New Murabba is by transit. This is largely because congestion limits the effectiveness of automobile travel in these simulations given the modeled capacity of roadways.

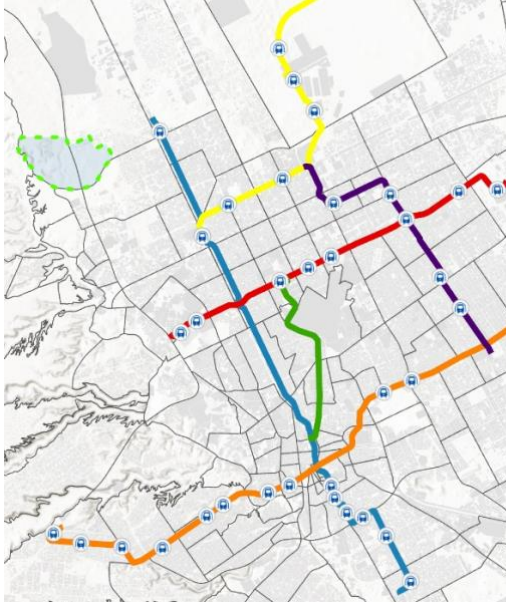


Figure 18. Current Metro system proposed in Riyadh

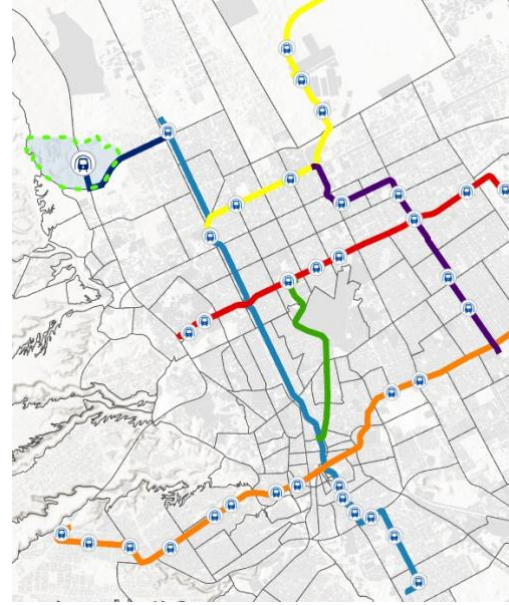
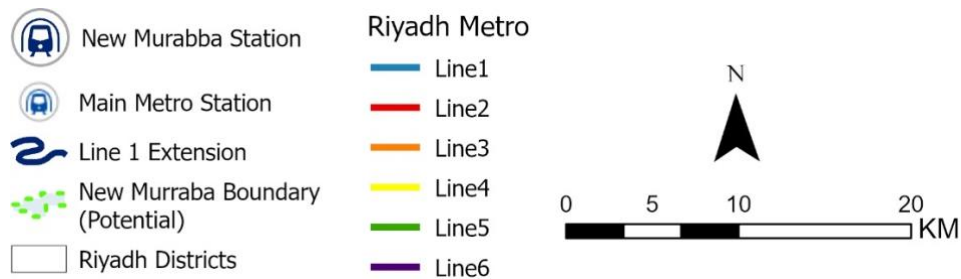


Figure 19. Metro station proposed with the New Murabba project



The RCRC travel model results indicate that extending the metro service to the New Murabba project provides the opportunity to reduce the energy use of travel by 1% for the entire city and for all trips, as compared to the reference scenario without the New Murabba and without the associated extension (Figure 17).

With a metro service extended to The New Murabba, the proposed development's visionary new downtown could achieve its goals without increasing the energy use of travel. However, this accomplishment was simulated as a consequence of high congestion on the road network (albeit reduced congestion from without the Metro, see Figure 20); if the road network were substantially expanded to further accommodate the new project there would be less congestion, more driving, and an associated increase in transportation energy use.



Figure 20. Level of service on roadways with the New Murabba project and with added METRO line

13 Findings from the New Murabba scenario

Households in total use larger dwellings in response to the increased supply of housing in The New Murabba Scenario, increasing domestic electricity consumption. This is a choice model response, so there is an associated quality-of-life benefit due to the higher supply of housing and resulting larger average dwelling size. The response is different for the different nationalities. Saudi households, on average, can take advantage of the villas provided in the development project (and will, based on their calibrated preference for housing type and size), and the shift to larger villas leads to more energy consumption. Non-Saudi households, in aggregate, choose more of the apartment buildings in the development, which is a more energy efficient dwelling type, leading to less total energy use by non-Saudis.

Employment and housing shift toward the project's non-centralized location. This leads to more travel, leading to increased energy use, overwhelming the roadway capacity in the surroundings of this project. The New Murabba's impact on the consumption of travel energy use is around 27 times larger than the impact on domestic energy use.

The transportation network struggles to accommodate the travel from and to opportunities in The New Murabba. Large traffic volumes and severe congestion is predicted in 2030 in and around The New Murabba development with the current planned transportation network. The simulation of spatial economic patterns shows that the development will be reliant on and interacting with the rest of the city's economy and the rest of the kingdom and the world. Providing a good Metro service into the development enables this interaction with less energy use, while reducing congestion on roads into and out of the development. The detailed design of the development's own internal

transportation network is important, but the simulation shows that the connections to the rest of Riyadh are critically important.

The increased energy use in transportation is contrary to the goals of the project, city, and kingdom. The high congestion is also potentially undesirable and could limit the ability of Riyadh to sustain its high growth rate, which was exogenously specified and not modelled as elastic to conditions in these scenarios. One possibility to mitigate these problems is to provide a good metro service into The New Murabba, so that the project is better connected to the city with higher transportation capacity and lower per-trip energy use. The calibrated RCRC travel model responds to the metro system leading to a simulated reduction of travel energy use by 1% across the entire city for all trips. Energy use could be further mitigated through fleet efficiency changes (e.g. electrification), which were not investigated.

14 Conclusions

The PECAS Riyadh model is a land use and transportation interaction model designed for simulating future scenarios in Riyadh. It includes a representation of future development, and the economic activity in the city locating within the development. Of particular interest is the construction of housing of different types in different locations, and the consumption of that housing by Saudi and non-Saudi households. The latest version adds a focus on the demand for electricity and other household energy within those houses, including the demand for energy for air conditioning systems.

The representation of housing and domestic electricity demand proves crucial. Distinct dwelling types and sizes are modeled based on household preferences, and an energy use model incorporates factors influencing household electricity consumption. Sensitivity tests reveal the model's responsiveness to dwelling characteristics, with the calibrated electricity use rates reflecting realistic consumption patterns.

The example project that was analyzed, The New Murabba, shows a planning scenario and public investment project that changes the residents' location, and affects their ability to live, function, and move around. The project provides new housing opportunities for residents of different dwelling types. The calibrated choice model for housing predicts that the villas provided in the project will be used more by Saudi households, with an associated increase in energy use, while the apartments will be used more by non-Saudi households, with an associated decrease in energy use. This residential self-selection is beneficial in a choice-model utility sense, but the resulting environmental impact is potentially a concern.

A bigger environmental issue is the transportation impact. The project is proposed in a non-central location, and the residents and businesses that move into the location in the simulation still interact with the rest of the city, the rest of the Kingdom, and the world economy, based on the model's calibrated relationships established when the input-output model of the economy was combined with the other data sources to develop the base year (2016) spatial economic model. Unless there is a substantial shift in the Kingdom's economic relationships, and in business and household willingness-to-pay functions between 2016 (the calibration year) and 2030 (the year The New Murabba is proposed to be complete), there will be substantial trips, travel, and shipments to and from The New Murabba. This could lead to severe congestion, accompanied by an increase in transportation energy use.

The simulation of a modified transportation network that includes a Metro station and substantial metro service to the project was quite successful in mitigating this impact in the model. This allowed the residents and businesses in the development to interact with each other in shorter trips but then interact with the rest of the city with a 50% AM mode

split to transit. This transit mode split is achieved partly because the roadways are still quite congested, making driving to and from The New Murabba unattractive. As a result, there is a net reduction in transportation energy use in this modified scenario. Whether this is realistic or not depends on whether the leaders and residents of Riyadh are collectively willing to accept this amount of congestion on the roadways and resulting shift to transit for longer trips and walking and biking for short trips. The announcement (Saudi Press Agency, 2023) indicates that the New Murabba will follow a people-centric design and be powered by its own transportation network, necessary daily services will be accessible through a 15-minute walk or bike-ride; the model simulation suggests that residents will take advantage of these walk and bike opportunities if they live in the new development, while driving or taking transit for the longer trips to other destinations.

The model forecasts increased household energy use in the New Murabba scenario. The demand for domestic electricity increases due to changes in housing structures, locations, quantities, and housing sizes, emphasizing the need for robust energy infrastructure to support the evolving cityscape. While the New Murabba promises transformative urban development, this paper highlights the intricacies involved in balancing housing, energy, and transportation dynamics. Comprehensive planning, adaptive policies, and sustainable transport solutions emerge as imperative to ensuring Riyadh's future growth aligns with its demographic, economic and environmental aspirations.

15 Future research and application

The large growth rate for population and employment was an assumed input to the model, following observed recent growth trends and published visionary growth documents. The New Murabba project contributes to accommodate this growth, but the overall growth anticipated even over 10 years is much larger than the capacity of proposed project. The PECAS framework produces top-level benefit measures, representing consumer surplus household benefits and producer surplus employment benefits. The evolution of these top-level measures over time could be investigated to provide some insight into whether the growth projection is likely or reasonable. As a city or region grows, the benefit measures can improve reflecting the larger number of opportunities that are available in a larger city, but only to the extent that travel conditions allow residents and businesses to take advantage of the opportunities, after accounting for travel costs including transportation congestion and delay, and the resulting higher rents paid in more accessible locations. The model could be used to investigate different growth scenarios but also provide some insight as to what types of spatial policies and projects regarding housing and other infrastructure (roadways, Metro, non-residential space) are best suitable to encourage and support the envisioned growth rate. The New Murabba project's design and location could attract a different mix of industries and households to Riyadh, with an associated change in the occupation mix (and skills) of residents. The model's top-level benefit measures provide information that could be used to predict changes in the mix, size, and other attributes of Riyadh's growth with (and without) the New Murabba project.

The model could be used to investigate massively expanded road capacity serving The New Murabba. Such a scenario could potentially show much lower congestion levels, but would also probably show higher energy use, since the mode-split to transit is partially supported by the congestion. Other scenario possibilities could also be investigated, such as the use of tolls to replace congestion's role in shifting people's trips to public transit.

In general use (beyond The New Murabba), the model could be used to pinpoint potential growth problems, in spatial and categorical detail. When high growth scenarios

are simulated into the future, the high demand for housing and high demand for transportation is balanced against the supply, and the resulting supply-demand relationships can generate simulated high housing prices and simulated high transportation congestion. Analysts who investigate the locations of high prices and high congestion can drill down into the model's detailed functions, to understand the nature and causes of these impacts, and design mitigating measures for implementation in the future city. These mitigating measures could also form inputs into a revised modelling scenario, repeating the process.

A more advanced transportation demand model in Riyadh should be developed and coupled with the Riyadh PECAS model. Such a model would enable infrastructure planning to avoid and mitigate congestion and allow travel, and the integration with the spatial economic model described here would permit an investigation of the economic benefits when improved transportation systems control or direct the growth of congestion and the resulting shift towards public transit and other non-auto modes of travel. The combination of a more advanced travel model and the parcel-by-parcel space development module of PECAS would also allow an investigation of the efficiency, equity, and effectiveness of sub-TAZ development patterns. In this paper we described the larger shifts in patterns of housing and electricity consumption, and travel; but we know from personal communications that integrated land use and transportation models are often used in a more technocratic (and behind-the-scenes) way to fine tune optimal patterns of development zoning and transportation infrastructure. A more advanced transportation model could also be better positioned to investigate other supporting transportation policies, not just major infrastructure construction, such as road tolls, changes in gasoline taxes, and electrification.

Future improvements in the PECAS Riyadh model itself could include incorporating the 2022 census data, increasing the number of household categories to account for different household sizes and income, adding labor supply elasticity into the model (and representing spatial patterns of residents' occupations), and including an endogenous model of international immigration for different occupations and types of non-Saudi households, along with an intranational migration for Saudi households that is responsive to simulated regional economic performance from the top-level PECAS benefit measures. Evaluating equity considerations, especially in terms of the displacement due to redevelopment (e.g. gentrification) could be a consideration when improving the categorical resolution of the model. The model should be validated against new data as it becomes available, such as the 2022 census data; calibrating and validating explicitly over a series of years is always desirable although it can take significant resources.

The Riyadh PECAS model is positioned to explore different possible ways of incorporating the rapid growth envisioned for Riyadh city, from planning, socio-economic, and transport perspectives. The model can be used to assess impacts, and explore the set of possibilities, for future developments, providing an analysis system to investigate development projects in Riyadh, as well as policies pertaining to land use, transportation, emissions, energy, housing, adjustments in the economic trends, regulations and taxation. This model supports a long-term vision of Riyadh, providing foresight that can lead to more effective long-term planning.

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Author contribution

The authors collaborated throughout the development of this paper, with the following primary contributions: conceptualization – A. Muhsen, J. E. Abraham, J. D. Hunt; data curation – A. Muhsen, J. E. Abraham, G. Fuenmayor; formal analysis – J. E. Abraham, P. McMillan; funding acquisition – A. Muhsen; methodology – J. D. Hunt, J. E. Abraham; software – J. E. Abraham; supervision – A. Muhsen; visualization – G. Fuenmayor, P. McMillan, A. Muhsen, J. E. Abraham; writing – original draft – G. Fuenmayor, J. E. Abraham, A. Muhsen; writing – review & editing – A. Muhsen, J. E. Abraham, J. D. Hunt.

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