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Transitioning to low-carbon suburbs in hot-arid regions: A case-study of Emirati villas in Abu Dhabi

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ABSTRACT

The continued and global popularity of single-family homes indicates that a scalable, yet regionally appropriate strategy for achieving zero-carbon suburban development is needed in the coming decades. This need is especially critical in the hyper-arid region around the Arabian Gulf where per-person carbon emissions are among the highest in the world. Using geometrically sensitive simulation models for a household's building energy, water, and automobile use, this paper uses Emirati neighborhoods in Abu Dhabi, UAE as a case study to estimate emissions for a baseline and set of future possible scenarios towards transitioning single-family households in the region to low, and eventually near-zero operational carbon emissions. An analysis of the combined impact of energy efficiency gains through (1) technology adoption and better design, (2) carbon intensity reduction from renewable energy transitions, and (3) carbon sequestration from parcel scale tree planting is presented. From a baseline CO₂ emissions of 64.3 tons per household per year for new construction, the study finds future emissions potential reductions of 33.7%–49.0% from improved house design, 98.1% from electrification and solar energy sourcing, and 99.4% from combined design and technology improvements. This study also finds that if the water-energy nexus in Abu Dhabi transitioned to solar-powered, reverse-osmosis desalination, trees would become net carbon sinks (0.6–1.9 kg CO₂/m²/yr). As a result, in the future, low-density neighborhoods with dense areas of tree planting may become a sustainable housing typology when measured by net operational emissions. This fact would upend multiple current assumptions by Western planners about sustainable transitions for arid regions.

1. Introduction

The need to transition society to a near-zero carbon future is well established by scientists and accepted by the majority of city, state, and national governments [1]. It has also become evident in recent decades that a majority of these emissions, typically 65%–85%, derive directly or indirectly from household consumption [2–5]. Comparative studies have further shown that carbon emission rates tend to be higher for detached, single-family households due to increased driving and building energy use [6–9].¹ In response, the urban planning and design disciplines have advocated for higher density, walkable, mass-transit oriented design solutions as the most sustainable housing form [10–12]. The reality, however, is that single-family homes continue to be the housing typology of choice for not only the majority of American families [13,14], but for a growing number of families around the world

[15,16]. It is imperative, therefore, that if global annual emissions are to rapidly decline over the coming decades, and reach near-zero by the last half of the century [17–20], scalable, yet regionally-appropriate strategies for achieving near-zero carbon, single-family households, must be developed [21].

The need for sustainable single-family household design is especially critical in the wealthy, hyper-arid region around the Arabian Gulf, where per-person emissions rates are among the highest in the world [22]. These emissions are driven in large part by the villa based, suburban neighborhoods [23,24] in cities of the Gulf Cooperation Council (GCC) nations, which demand significant amounts of energy for air-conditioning and desalination of water for indoor and landscaping uses [25–27]. Research and design of low (and zero) carbon housing in this region is less developed than in the West, but the recent construction of several sustainable prototypes in the region highlights a

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¹ There is increasing debate in the planning literature around this topic. A number of recent studies have shown emissions rates of low-density and high-density housing to be nearly identical or even lower for low-density housing (Du et al., 2016; Perkins et al., 2009).

burgeoning field.

This paper, using the suburban Emirati villa neighborhoods in Abu Dhabi as a case study, seeks to answer the question of how single-family house typologies in a hyper-arid region can achieve near-zero carbon operational emissions, or even carbon-neutrality.

This study aims to extend the empirical work already being done in this region through built prototype houses in the following key ways:

- Integrate the three primary operational energy (OE) uses driven by household scale activity: (1) building cooling, plug, and equipment loads; (2) water desalination, pumping, and heating; and (3) automobile driving – collectively referred to as BWA.
- Normalize OE to operational carbon emissions (OC) for each BWA component and, where appropriate, by the number of trees required to offset emissions (TO).
- Investigate the relative and combined impact of technology-based solutions versus design-based solutions.

This paper describes the history of Abu Dhabi's Emirati neighborhood development and provides an overview of research for (1) low-energy and net-zero villa typologies in the region, (2) advances in solar photovoltaic technology (PV), and (3) the current state of neighborhood carbon sequestration studies. Next, it describes the methodology and materials used to define and simulate scenarios aimed at lowering household OE and OC. The OC results of each scenario is summarized for each BWA component, as well as the total aggregate household emissions, net energy production of the household, and TO requirements for achieving zero-carbon operations. The discussion section begins with limitations and future research. Next, the use of trees as a metric for carbon offsetting and the resulting future role of landscape design in the region is discussed. Finally, the relative costs of transitioning to low-carbon technologies and the efficacy of current building standards in Abu Dhabi is described.

2. Background

2.1. Neighborhood development

GCC cities have seen an explosion of urban growth since the 1950's due to the discovery of hydro-carbon reserves in the region. Often referred to as 'manufactured' urbanization, development in these cities was largely influenced by Western planning and design models, including urban grids and low-density residential neighborhoods [28,29]. Initially built by oil companies, the villa neighborhood typology consists of large, individually walled plots (1000–2000 m² or more) with detached, single-family homes. This housing form rapidly became the 'ideal' and 'modern' model that local communities aspired to, and serves as the dominant typology for Emirati housing today [30]. The preference for villas remains robust in the GCC [31]. In terms of total housing share, villas constituted roughly 30% of new construction in Dubai and 60% in Sharjah from 2003 to 2011 (by floor area) [32]. In Abu Dhabi specifically, villa-based neighborhoods occupy over 55% of the current built-area (author calculation based on GIS data) (Fig. 1). Considering that villa typologies are such a highly preferred residential typology in the region, ensuring that villa households can achieve low-carbon futures is critical towards lowering national carbon footprints and maximizing the utilization of land for productive purposes.

2.2. Low-energy villas

Design and testing of low and near-zero carbon single-family home typologies has been underway in the Western context for many decades [33–36]. Low-energy housing in the Arabian Peninsula has a shorter history, but a number of prototypes have recently been built, including the SQU EcoHouse (2011) in Oman, the Baytna-Qatar Villa (2012) in Qatar [37], and the EcoVilla in Masdar City [38]. Regionally specific

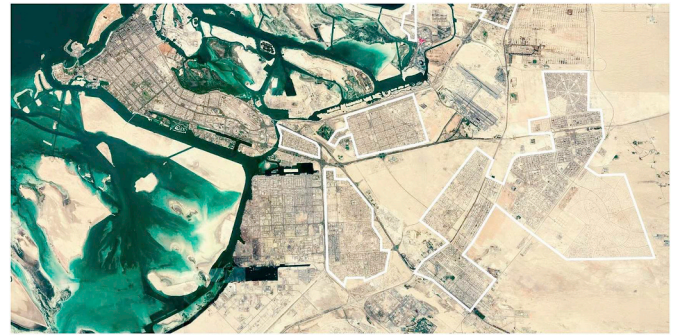


Fig. 1. Villa Neighborhoods in Abu Dhabi (white outline).

energy standards have also been developed, including Estidama by the Abu Dhabi Urban Planning Council (2013), which requires all new villa's to meet Pearl 1 standards within the five Pearl rating system [39].

2.3. Advances in solar technology + potential for carbon sequestration

The transition towards low and zero-carbon housing in hyper-arid regions is aided by two environmental conditions. First, a high insolation rate of 2100 W/m²/year with an average of at least 11 h of sunlight per day, provides consistent solar electricity [40]. Recent improvements in solar panel manufacturing has brought emission factors down to ~10 g CO₂/kWh [41], with ~5 g CO₂/kWh likely in the near-term [42]. For comparison, the current emission factor for grid electricity in Abu Dhabi is 470 g CO₂/kWh [43]. Solar is also rapidly becoming the cheapest energy source in the region, with recent bids going below \$0.02/kWh for utility scale projects [44,45], far less than the \$0.08/kWh required to produce fossil-fuel based electricity for the current grid [46]. This price discrepancy and environmental advantage has led to recent initiatives such as Dubai's Clean Energy Strategy 2050, which seeks 75% energy from solar by 2050 and mandates roof-top solar installations [47]. Second, the lack of pre-existing vegetation within suburban Emirati neighborhoods results in large open spaces which could be planted with fast-growing trees to capture carbon [48–51]. When supplied with water from solar-powered, reverse-osmosis desalination plants (SRO), trees have the potential for significant net carbon sequestration relative to OC, as this paper will demonstrate. Studies of net carbon fluxes from existing neighborhoods have found that currently vegetation (tree, grass, soil) only captures 1%–4% of emissions [52–54]. Missing in these papers, however, is a calculation of potential emission reductions from better housing design and technological transitions. This paper aims to fill this gap, by testing likely scenarios for future household scale emission reduction and carbon sequestration together.

3. Materials and methods

This study has three phases. The first phase sets eight total scenarios – six current and two future scenarios – that test the potential impact of improved design and/or technology towards transitioning to low or near-zero carbon household operations. The second phase runs each scenario's parameters through validated simulation models to estimate carbon emissions. Sequestration rates for each scenario are based on empirical research. A sensitivity analysis is also conducted. The third phase briefly considers the economic and regulatory feasibility of implementing the proposed technologies and design changes.

² Solar-to-battery balancing has been investigated and shown to be a viable option in desert climates [57–59].

Table 1
Scenario descriptions.

Scenario	Descriptions		Technology Categories				
	Design Scenario	Technology	Insulation Std. [d]	Appliance Std. [e]	Water Source	Electricity Source	Car Engine Type
S1 (T1-D1)	Typical House (D1) [a]	T1 Baseline	Estidama Pearl 1	Estidama Pearl 1	MSF Desalination	Current Grid	Gasoline
S2 (T1-D2)	Improved House (D2) [b]	—	—	—	—	—	—
S3 (T2-D1)	D1	Full Electrification (T2)	—	—	RO Desalination	Solar + Battery	Electric
S4 (T2-D2)	D2	—	—	—	—	—	—
S5 (T3-D1)	D1	Electrification + High-Efficiency	Passive House	High-Efficiency	—	—	High-Eff. Electric
S6 (T3-D2)	D2	—	—	—	—	—	—
SS1	D1	S3 with Improved Solar	Estidama Pearl 1	—	—	Future Solar	—
SS2	Compact House [c]	S6 with Smaller House, Improved Solar + RO	Passive House	—	Future RO Desal	—	—

[a] 75 m²/person; no house shading; 15% aggregate window-to-floor ratio; thermostat = 22°C; [b] 50 m²/person; house shading; 10% aggregate window-to-floor ratio; thermostat = 24°C; [c] 40 m²/person; house shading; 10% aggregate window-to-floor ratio; thermostat = 24°C; [d] Includes wall, roof, slab, and window insulation values, infiltration rates; [e] lighting efficiency, and water appliance standards.

3.1. Existing and future low-carbon scenarios

The first phase of the study involved establishing scenarios which could be reasonably compared to one another to understand the relative impact factors of future technology and design on operational carbon emissions at the household scale. We defined three technological scenarios (T1, T2, T3) to test the impact of technology alone on net emissions. Two formal house design and thermostat set-point scenarios (D1, D2) were then combined with each technology scenario for six total scenarios (S1 through S6). The key parameter categories, standards, and technologies assumed for each scenario are shown in Table 1. See Appendix A for a comprehensive list of parameters and values.

3.1.1. Technology scenarios

The first technology option (T1) used Estidama standards for construction insulation values, and lighting and appliance efficiency. Occupant water-use and driving behavior were set using empirical studies from the region [55,56].

The second technology option (T2) tested the potential emissions reduction from transitioning from gasoline cars to electric cars and from natural gas driven multi-stage flash desalination (MSF) to electric pump driven reverse-osmosis (RO) desalination. All electricity supply was modelled from roof-top or ground-mounted solar panels plus battery storage. It was presumed, though not simulated, that households could perform adequate load-balancing with a 40.5 kWh household battery system in conjunction with two electric automobile battery systems.² This scenario sets an upper bound in operational carbon emissions that existing Estidama standards would permit under an electrification scenario. The third technology option (T3) tested the additional potential (post-electrification) for emissions reductions from efficiency improvements that meet the Passive House standard [60], namely: improvements to building façade insulation and air-tightness, more efficient appliances and fixtures, and replacement of incandescent bulbs with high-efficiency LEDs.

3.1.2. Design scenarios

Two design options were developed to test the potential impact of formal house and landscape design parameters which define the villa typology. These include house size, window size and location, tree number and location, and thermostat set-point. The latter is included as it is a primary behavioral parameter that interacts with room size and solar gain in a space to determine overall human comfort [61,62]. The design parameters were combined with the three technology scenarios

to test the combined impact of technology and formal design on net carbon emissions.

The first design option (D1) set a baseline that adheres to Estidama Pearl 1 Rating Standards for window-to-floor ratio. Floor area per person was set using the upper range of average house sizes in Emirati neighborhoods [63] divided by the average family size. Given the abundance of houses in Abu Dhabi with few to no shade trees, the D1 scenario assumed no landscaping. The second design option (D2) reduced floor area to the lower bound found in Emirati neighborhoods and set window-to-floor ratio to a lower limit defined by daylighting studies from similar contexts [64]. Thermostat temperature was raised from 22 to 24°C.

Both design options assumed a two-story, rectangular form, with 1–1.5 ratio of width to length. This provides a generic form, generally applicable to arid regions.³ Fig. 2 shows the building and landscape design for both scenarios. The house is conservatively oriented with longer exposures faced East-West, which generates the maximum solar heat-gain [65].

Throughout the technology and design options, the amount of appliance usage and driving behavior was unaltered. This allowed the authors to study the potential impact of technology and design alone, with no changes to the lifestyle of the family, except those imposed by living in a smaller than average house, though house size remained within typical ranges found in Emirati neighborhoods.

3.1.3. Special Scenarios

Two final scenarios were simulated which modified previous scenarios. The first Special Scenario (SS1) tested the impact of future improvements to solar panel manufacturing in the form of higher efficiency (21%) and lower carbon factor (6 g CO₂/kWh) [42,66,67]. This change was applied to S3, the first full electrification scenario. It tested the benefit of improving the carbon factor of solar-PV production instead of improving building insulation, appliances, and other technologies which are seen in S6, and are likely costlier to implement. By extension, this scenario also tested whether current Estidama regulations are stringent enough to allow for a transition to low carbon villa designs assuming electrification of desalination and automobile propulsion and future reductions to the solar-PV carbon factor.

The second Special Scenario (SS2) tested for the same solar panel

³ Test simulations using EnergyPlus revealed only a 5% difference in cooling demand between a square, L, and courtyard shaped footprint when floor area and all other variables were held constant.

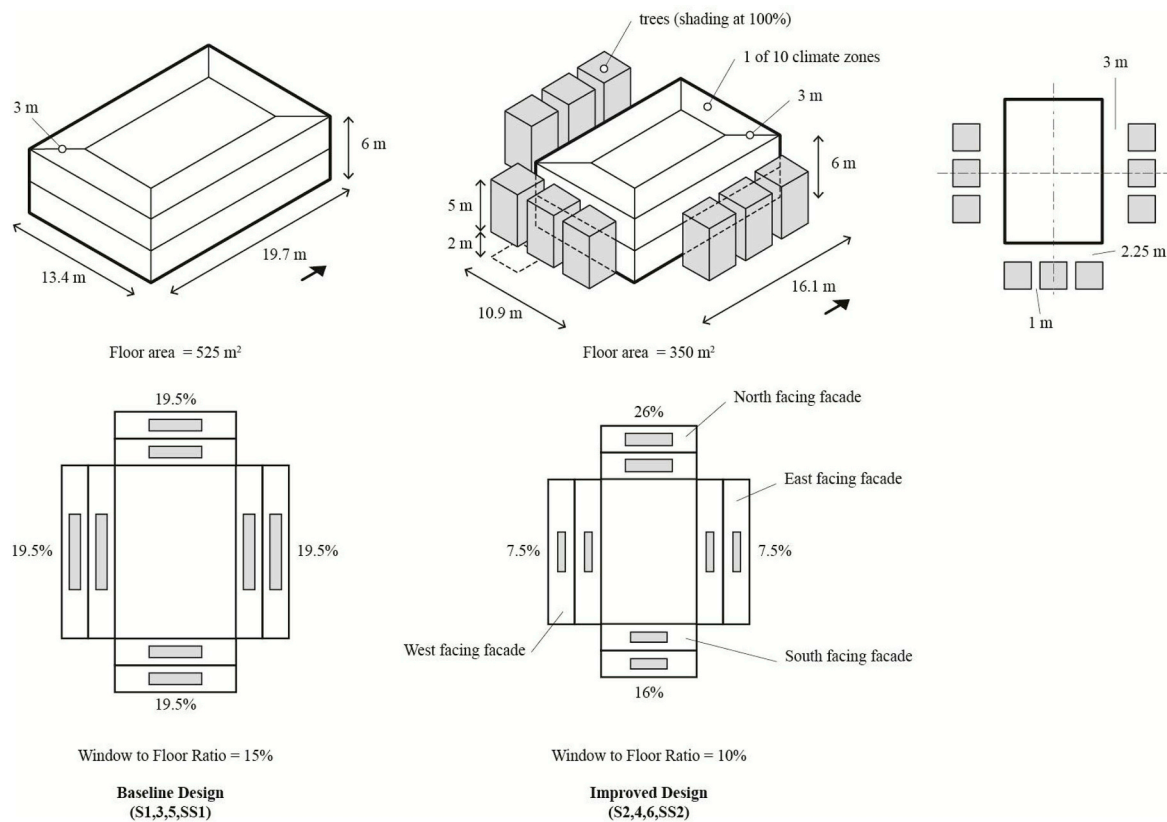


Fig. 3. Operational Emissions (Yearly Per Person): Log Scale
Note: Log scale is used for legibility of relative results within each scenario. See Visual Abstract for same results plotted against an absolute scale. Sequestration = 2000 m² plot (Fig. 4), 100% canopy coverage, averaged sequestration of four best tree species (Appendix B).

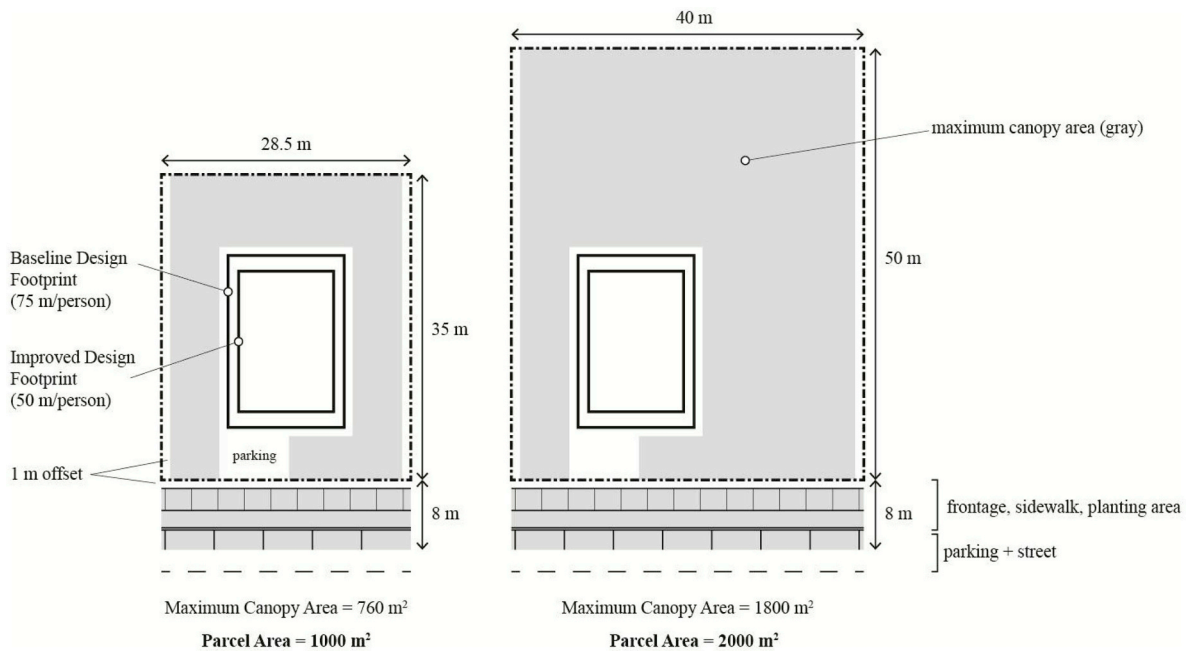


Fig. 4. Maximum canopy area of small and large Emirati parcels.

improvements as S1, plus the following additional improvements that are reasonably likely in the near future:

- Space per person lowered by an additional 20%, from 50 to 40 m².⁴
- Equipment load lowered by 25% from 3.9 to 2.9 w/m² [69].
- RO desalination energy factor lowered from 4.0 to 2.0 kWh/m³ water, the projected level of “near-horizon” improvement potential using hybrid approaches [70].
- Embodied carbon (EC) from battery production reduced by 45% from 14.5 to 8 kg/hh/yr, in line with the solar carbon factor reduction.

3.2. Energy, water, and transport models

The method used in this study aims to understand the relationship between factors of climate, house and landscape design, and technology. Emissions resulting from household members’ daily activities are calculated irrespective of the specific geographic location of emissions. This method differs from more strict metabolism studies that use a discrete spatial boundary to limit measurements of carbon fluxes [71,72]. Our approach, used successfully in previous studies of household scale metabolism [73,74], allows a clearer understanding of what activities are responsible for a given emission source, where they originate from, and thus how best to reduce that emission. That said, this paper does not offer a full Life Cycle Assessment (LCA) study, and the results should be considered in light of this. Final emissions calculated in this study include:

1. CO₂ emissions from direct energy use for building air-conditioning, lighting, and equipment use, excluding transmission losses.
2. CO₂ emissions from direct energy use for the desalination and distribution of potable water and for hot-water heating, including household leakage and municipal distribution losses.

3. CO₂ emissions from direct energy use for daily automobile use. Seasonal, intercity train, bus, and plane travel is ignored.
4. CO₂ emissions from the manufacturing of solar-panels and lithium-ion batteries for household scale storage (embodied emissions).

All models were simulated using Python coded components in Grasshopper for Rhinoceros, allowing geometrically explicit simulations for building size, shape, window areas, and tree shading.⁵

3.2.1. Building energy

EnergyPlus was used for building energy simulation including heating, cooling, ventilation, lighting and plug-and-process loads. It has been validated and is in continual development by the US Department of Energy [75–77]. The open-source toolset and middle-ware Ladybug and Honeybee was used within Grasshopper to generate, run, and return results from EnergyPlus files [78,79]. Heating was ignored as most houses in Abu Dhabi do not have heating systems due to the hot climate. In the result section, plug and process loads were combined under equipment loads, while ventilation, fan, and pump energy loads were combined under cooling loads.

3.2.2. Potable water + how-water heating

Ninety-nine percent of potable water in Abu Dhabi comes from desalinated sources [80]. For this sector, the total energy intensity was calculated using the following parameters:

- direct energy for desalination
- conveyance energy and water-mains losses
- appliance or fixture efficiency (liter per use or minute of flow)
- appliance use rate (cycles or minutes of use per person per day)

⁴ Still at or above the average floor space for developed economies like Japan, France, Spain, Italy, Sweden, though below the United States, Canada, and Australia [68].

⁵ Grasshopper is a visual scripting environment which allows three-dimensional digital user inputs from Rhinoceros 3D to be used in numeric simulations (through Python’s math functions), as well to be converted for calls to external software packages. Rhinoceros 3D is an industry standard three-dimensional modelling software package used by architects, landscape architects, and urban designers.

- household appliance and faucet leakage rate

Parameter values for desalination and conveyance were conservatively estimated from currently operating systems [81,82]. Appliance efficiency rates were set using Estidama standards or currently available technologies depending on scenario. Occupant usage rates were set using a detailed study of 151 households in Abu Dhabi using flow sensors [56].

Hot-water energy demands were calculated using the Water Heater Analysis Model (WHAM) [83]. It was assumed that all water for dish-washing, clothes washing, showers, and half of the faucet water was used at 40 C. Water main temperature was calculated using the algorithm developed by Christensen and Burch [84] and implemented in Honeybee/Ladybug. A mixing ratio of hot-water and water from the municipal supply-system was pre-calculated to determine the water volume drawn from the hot-water tank to achieve a typical desired temperature at the fixture [85,86].

Water use for solar panel cleaning, while historically a source of additional water demand in the MENA region, was ignored in this study due to recent improvements in both water [87] and non-water [88,89] based cleaning systems. Studies have found that brushing or blowing is effective for cleaning panels in the MENA region [90].

3.2.3. Daily automobile use

Energy required for daily automobile use was calculated using the following parameters:

- average distance travelled per-person per-day
- average automobile occupancy rate
- automobile energy-efficiency rating

Data for transportation behavior was derived from a travel survey conducted in 2009 [55]. Average travel times by gender and age were used in conjunction with household demographics to estimate average travel distance per member for a typical Emirati family [91]. Car occupancy rates were not available for Abu Dhabi so the United States occupancy rate was substituted.

3.2.4. Solar + battery carbon

A key feature of this study is using the latest carbon emissions factor from recent solar panel manufacturing studies. First Solar Series 6 panels have been independently tested to generate 11 g CO₂/kWh supplied [41,92,93]. Carbon emissions for lithium-ion battery production is also rapidly declining due to improvements in manufacturing processes and the use of renewable energy sources. Because battery system sizing and micro-grid modelling is outside the scope of this study, this

study uses Tesla's recommended sizing for a large house. While net-metering would be required during portions of the year, this does not impact net carbon emissions from on-site solar systems per the carbon accounting principles defined by The National Renewable Energy Laboratory's Net-Zero Energy Buildings [94].

Results from lithium-ion battery manufacturing emissions studies still vary widely, from 38 to 356 kg CO₂-eq/kWh [95,96]. This study assumed the following parameters when calculating battery embodied carbon emissions:

- conservative (high) energy demands of 587 MJ/kWh for cradle-to-gate manufacturing [97].
- all mining and manufacturing processes electrified and supplied from solar energy with a carbon factor of ~30 g CO₂/kWh [98,99].
- gate-to-consumer transportation emissions ignored as they represent less than 1% of total emissions [100].

3.2.5. Carbon sequestration from trees

Net carbon sequestration from trees is possible in a coastal, arid environment when the water used for irrigation is supplied from SRO. To determine the average net sequestration from a group of typically occurring trees in Abu Dhabi, we selected nine species present in both Abu Dhabi's Public Realm Design Manual [101] and the U.S. Forest Service's CUFR Tree Carbon Calculator [102]. Abu Dhabi's reference evapotranspiration (ET_o) of 2437 mm/year was calculated for the climate station at Abu Dhabi International Airport (54.65 longitude, 24.43 latitude, 27, altitude) using the FAO's ClimWat 2.0 and ET_o 3.2 software [103,104]. Yearly water demand and resulting energy demand for RO desalination was calculated for a twenty year old specimen for each tree species using the Water Use Classification of Landscape Species (WUCOLS) method [105]. Net emissions (sequestration) was calculated as gross emissions from water desalination and pumping minus the carbon sequestered by the tree (Appendix B).

3.2.6. Energy + carbon balance

Energy demands and emissions for each BWA component were calculated first. The combined emissions for BWA was then aggregated to determine the total sequestration required to offset emissions for each scenario (Table 5). Finally, the additional energy needed for SRO to water trees for sequestration is added to total household energy demands, and a final calculation of the required space for solar-PV to match all demands is made (Appendix D). This calculation is done for each of the eight total scenarios. Table 6 provides a simple, single-factor sensitivity analysis of the major input parameters for S6. The authors set upper and lower bounds using reasonable assumptions for variance based on the parameters' characteristics and degree of certainty to

Table 2
Per person emissions from building energy use.

Scenario	Description	EUI	CO ₂ Factor [a]	Carbon Emissions [b] (kg CO ₂ /person/year)				Comparisons	
				Cooling	Lighting	Equipment	Total	% of S1	% Share
	Existing Villas [d]	349	470				12,302.3	186.5%	78%
S1 (T1-D1)	Estidama Pearl 1 Standards (EP1)	187	—	4250.6	1126.2	1219.8	6596.6	100.0%	72%
S2 (T1-D2)	EP1 + Smaller House (SH)	149	—	1939.5	750.7	813.1	3503.2	53.1%	57%
S3 (T2-D1)	EP1 + Solar	187	11	99.5	26.4	28.6	154.4	2.3%	86%
S4 (T2-D2)	EP1 + SH + Solar	149	—	45.4	17.6	19.0	82.0	1.2%	76%
S5 (T3-D1)	Passive House Standards (PH) + Solar	81	—	44.6	3.6	18.6	66.7	1.0%	81%
S6 (T3-D2)	PH + SH + Solar	71	—	24.3	2.4	12.4	39.0	0.6%	72%
SS1	EP1 + Improved Solar (IS)	187	6	54.3	14.4	15.6	84.2	1.3%	89%
SS2	PH + Smallest House + IS	64	—	10.4	1.0	4.0	15.5	0.2%	66%

EUI = kWh/m²/yr; % Share = category emissions divided by total BWA emissions [a] g CO₂/kWh from electricity supply (not including battery) [b] kWh/person/year = carbon emissions/emissions factor [d] Energy values normalized for 75 m²/person [26].

Table 3

Per person emissions from indoor water use.

		CO ₂ Factor [b]		Emissions (kg CO ₂ /person/year)			Comparisons	
		Heating	Desal	Water Heating	Potable Water	Total	% of S1	% Share
Scenario	Description							
	Existing Villas [a]	470.0	12,790.0	180.6	1803.4	1984.0	151.4%	13%
S1 (T1-D1)	Estdama Pearl 1 Standard (EP1) + MSF	470.0	12,790.0	119.7	1190.4	1310.2	100.0%	14%
S2 (T1-D2)	—	470.0	12,790.0	119.7	1190.4	1310.2	100.0%	21%
S3 (T2-D1)	EP1 + SRO	11.0	48.0	2.8	4.5	7.3	0.6%	4%
S4 (T2-D2)	—	11.0	48.0	2.8	4.5	7.3	0.6%	7%
S5 (T3-D1)	High-Efficiency Appliances (HEA) + SRO	11.0	48.0	1.7	1.2	2.9	0.2%	4%
S6 (T3-D2)	—	11.0	48.0	1.7	1.2	2.9	0.2%	5%
SS1	EP1 + Improved Solar	6.0	26.0	1.5	2.5	4.0	0.3%	4%
SS2	HEA + Improved Solar and Improved SRO	6.0	14.0	0.8	0.4	1.2	0.1%	5%

Yearly indoor water use per person for existing villas is $\sim 141 \text{ m}^3$, and for new construction with standard appliances is $\sim 93 \text{ m}^3$ [S1–S4,SS1], and with highly efficient appliances is $\sim 25 \text{ m}^3$ [S5,S6,SS2]. [a] Assumes electric resistance water heater at 0.9 COP [b] g/kWh for Heating and g/m³ for desalination.

Table 4

Per person emissions from car use.

		CO ₂ Factor [d]	Emissions [c]		Comparisons	
			Driving	% of S1	Total Share [e]	
Scenario [a]	Description					
	Existing Average Car [b]	194	1440.2	112.4%	9%	
S1 (T1-D1)	"Good" Efficiency Gas Car [f]	173	1281.5	100.0%	14%	
S2 (T1-D2)	—	—	1281.5	—	21%	
S3 (T2-D1)	Electric SUV + Solar	2.53	18.8	1.5%	10%	
S4 (T2-D2)	—	—	18.8	—	17%	
S5 (T3-D1)	High-Eff. Electric Car + Solar [g]	1.69	12.6	1.0%	15%	
S6 (T3-D2)	—	—	12.6	—	23%	
SS1	Electric Car + Improved Solar	0.92	6.9	0.5%	7%	
SS2	—	—	6.9	—	29%	

[a] All scenarios assume 11,500 km/person/year of driving at occupancy rate of 1.55 persons/car [b] Existing cars in the UAE have average fuel efficiency of 8.26 l/100 km [c] kg CO₂/per/yr [d] g CO₂/km [e] Percent share of total emissions for all categories across water, building energy, car use [f] UAE uses six fuel economy standards: Excellent, Very Good, Good, Average, Poor, Very Poor, See [Appendix A](#) [g] For comparison, an electric car powered from current grid in Abu Dhabi would have a CO₂ Factor of 7.24 g CO₂/km.

which the values assumed in the scenario are achievable.

4. Results

The results for each individual BWA sector are discussed first to highlight the key parameters driving lower carbon emission values in each area (Tables 2–4). The aggregated OC results are then discussed in relation to tree sequestration (Table 5).

4.1. Disaggregated results

4.1.1. Building energy (BE)

Taken individually the impact of (1) housing design, (2) insulation and technology efficiency, and (3) solar-PV energy sourcing can reduce OC by 53% (S1 to S2),⁶ 57% (S3 to S5), and 97% (S1 to S3) respectively. Replacing fossil-fuel based grid electricity with solar-PV electricity is clearly the most important factor in reducing emissions from building energy use. That said, housing design parameters such as shading, window-placement and size, and efficient use of space still have a role

⁶ Scaling of equipment loads for smaller houses may or may not occur. It is self-evident that moving a family from a larger house to a smaller house would not likely result in less appliance or electronics usage, though it would result in less lighting and cooling loads.

to play in lowering BE per person and thus OC as well (see 5.6 for further discussion). This study also indicates that as new technologies are implemented across all of the BWA sectors, the share of OC from BE may rise to as high as 89%, with building cooling being the dominant factor. Therefore, energy efficient housing design will remain a key strategy towards achieving near-zero household carbon strategies. Reducing energy use also lowers the number of panels and battery storage needed to meet power requirements, thus decreasing embodied emissions, material intensities, and increasing the ability to meet all operational energy needs with low-carbon renewables.

4.1.2. Indoor water (WE)

Recent improvements to water appliance efficiencies (S3/S4 to S5/S6) can reduce water use and hence emissions by 68%, and offers an immediate, near-term solution to reducing emissions from household water use. However, a much more significant reduction in emissions of 99.6% results from transitioning to solar-PV supplied RO (SRO) (S1 to S3). When combined, high-efficiency appliances and SRO reduces emissions by 99.8% (S1 to S5). This reduction significantly overshadows the limited ($\sim 5\%$) potential to reduce water use based emissions through behavioral modifications [106–108]. It should be noted that all desalination plants currently under construction or planned in the future will use RO processes [109]. Furthermore, there is reason to believe this trend will likely continue indefinitely until a full transition occurs, as RO is cheaper to produce and does not have the energy

Table 5
Household carbon balance.

Scenario	Household Emissions (kg CO ₂ /yr)			Household Emissions Offset Requirements [b]				% Plot Coverage by Canopy			
	Per Person	Per HH [a]	% of S1	Trees		Canopy (m ²)		Medium Plot		Large Plot	
				High	Low	High	Low	High	Low	High	Low
Existing Villas	15,726.5	110,085.2	171%	6116	1747	172,008	84,034	22633%	11057%	9556%	4669%
S1 (T1-D1)	9188.2	64,331.9	100%	3574	1021	100,519	49,108	13226%	6462%	5584%	2728%
S2 (T1-D2)	6094.9	42,678.6	66%	2371	677	66,685	32,579	8774%	4287%	3705%	1810%
S3 (T2-D1)	180.5	1278.0	2.0%	71	20	1997	976	263%	128%	111%	54%
S4 (T2-D2)	108.1	771.2	1.2%	43	12	1205	589	159%	77%	67%	33%
S5 (T3-D1)	82.3	590.3	0.9%	33	9	922	451	121%	59%	51%	25%
S6 (T3-D2)	54.6	396.4	0.6%	22	6	619	303	82%	40%	34%	17%
SS1	95.1	680.2	1.1%	38	11	1063	519	140%	68%	59%	29%
SS2	23.5	172.7	0.3%	10	3	270	132	36%	17%	15%	7%

[a]Assume family of 7 and includes embodied emissions of 14.5 kg/hh/yr from 40.5 kWh of household battery storage with 15-year lifetime manufactured with solar electricity. [b]Assumes sequestration of between 18 and 63 kg/tree/yr and 0.64 and 1.31 kg/m² canopy/yr depending on the mix of species used (either the four best or four worst species) (see [Appendix B](#)) Note: Grayed numbers are calculated assuming SRO water supply for trees and as such are provided for illustrative purposes only.

supply insecurity issues that MSF does [110–113].

4.1.3. Automobile (A)

The ability of solar-powered electric vehicles to reduce carbon emissions by 98.5% (from S1 to S4), without any change to driving

behavior, suggests that near-term policies aimed at carbon reduction from driving should focus on supporting the rapid transition to electric vehicles [114,115]. These policies could supplement a longer-term strategy towards lowering automobile dependence and per-person driving distances through improved land-use and transportation

Table 6
Sensitivity analysis for S6 (passive house + Solar-PV + RO desalination + electric car).

Input Parameters			Impact on Final HH Carbon [a]					
Parameter	S6 Value	Units	Variance		Decrease	Increase	Sensitivity	Estimated Maximum Impact
			% Decrease	% Increase				
Design Parameters								
Floor Area per Person (house size)	50		25	50	66	131	2.6	33%
Window to Wall Ratio [b]	Varies	Varies	10	25	3.1	8	0.3	2%
Tree Shading (no auto shading)	Varies	Varies	100	0	0	3.5	0.0	1%
Household Behavioral Parameters								
Energy Transition (grid to solar-PV)	100%	% energy from Solar	50	0	0	8166	163.3	2060%
Indoor Water Use [c]	448	l/hh/dy	25	50	2	4.3	0.1	1%
Driving Distance [d]	31.5	km/per/dy	10	50	9	44	0.9	11%
Vehicle Occupancy [e]	1.55	ratio	50	50	29	88	1.8	22%
Cooling Set-Point [f]	24	Celsius	3	3	39	60	4.8	15%
Car Engine Type (ICE to electric)	100%	% driving with electric	50	0	0	2517	50.3	635%
Electric Car Model (choice) [g]	15.4	kWh/100 km	50	100	44	88	0.9	22%
Household Technology Parameters								
Air Conditioning COP	4.5	ratio	25	25	53	33	2.1	13%
Plug Loads	3.9	W/m ²	50	50	62	61	1.2	16%
Lighting Loads [h]	1.5	W/m ²	0	100	0	24	0.2	6%
Household Air Tightness [h]	0.001	m ³ /s/m ²	0	50	0	14	0.3	3%
Insulation Values [h]	Varies	w/m ² /k	0	50	0	13	0.3	3%
Window Shading (auto or manual)	Varies	NA	100	0	0	21	0.2	5%
Carbon Factor for Solar Panels	0.011	kg CO ₂ /kWh	50	50	196	196	3.9	49%
Utility Adoption Parameters								
RO Desalination Efficiency	4	kWh/m ³	25	25	2	2	0.1	0.5%
Desalination Transition (MSF to RO)	100%	% water from RO	50	0	0	1123	22.5	283%

[a]Sensitivity is calculated by dividing the largest absolute increase or decrease per parameter by the percent change. Maximum potential impact is calculated by dividing the largest magnitude change (decrease or increase) by the aggregate household's emissions value for S6 (396.4 kg CO₂/hh/yr). Results assume linear relationships which will not be true for certain parameters. [b]Window-to-Wall Ratios are already near or at legal minimums. Window area increase is more likely but Estidama standards limit upper range. [c]Standard deviation from Waterwise study used to set upper threshold. [d]Driving distance is more likely than not to increase with autonomous vehicles and increased expansion of suburbs in Abu Dhabi. [e]Shifts to autonomous shared mobility solutions could increase occupancy significantly. Likewise, private ownership of autonomous cars could lead to lower occupancy rates as a result of 'empty' miles. [f]Based on ASHRAE 55–2013 [g]There is a wide range of efficiencies in electric cars based on size and technologies deployed (see: www.fueleconomy.gov) [h]For cost-benefit reasons these values are already near or at their minimums.

planning.

4.2. Aggregated results, sequestration, sensitivity analysis

The household carbon balance results from this study show that to achieve carbon neutrality from a combination of lower emissions and sequestration from trees, it is necessary to electrify both automobiles and desalination and to supply all electricity demands with renewable energy. Moreover, zero-carbon emissions would be achievable with no changes to a household's consumption patterns (eg. driving distance per year) or lifestyle other than possibly living in a smaller house, and/or raising the thermostat set-point by two degrees. This is an important finding given that a number of studies have shown long-lasting shifts in human behavior can be difficult to achieve [108,116].

5. Discussion

5.1. Study limitations

While this study combines a range of parameters contributing to household emissions, there are several limitations that should be considered.

1. The assumption that lithium-ion battery manufacturing can be fully electrified is speculative. Currently, roughly 60% of cradle-to-gate energy use is from electricity [97], mostly for cell manufacturing, with total energy use ranging from 3.1 to 586 MJ/kWh [97,117]. The remaining energy is used for material production and requires mostly fossil-fuels [118]. However, recent efforts to transition material production processes to electric heat sources [119–121] makes it reasonable to assume near-term battery manufacturing can become fully electrified.
2. Embodied carbon (EC) from house construction [8,122–126], transportation infrastructure construction [127–130], and both gasoline and electric car manufacturing [114,117,118,131] can constitute a significant portion of total life-cycle emissions (LCE) [132]. Moreover, if sustainable energy and electrification transitions do not occur as rapidly as we project are possible in housing construction and manufacturing supply chains, EC will increase as a share of LCE, potentially by a significant amount. The results of this paper should be considered in light of this fact. However, this paper does not factor in EC for a few reasons. First, a study of equal comprehensiveness to the OE study done here is outside the scope of a single paper. Second, data and existing LCA studies in Abu Dhabi and the GCC are currently limited for all sectors. Only one high-quality LCA study for low-energy villa construction in the GCC region was found [122]. More data is needed before a projective study of housing and transportation EC in the GCC can be done. Third, within the broader literature on EC for low-energy and Passive House construction, there remains a large degree of uncertainty in findings. This problem has been repeatedly noted in the literature [123,133,134]. Using recent LCA studies for house construction (Appendix F), the authors find that depending on the accounting method, geographic location, house size per person, and construction type, EC could range from 35 to 23,300 kg CO₂/per/yr, and require from 5 to 4600% of a small parcel's potential canopy area to offset (Fig. 4). Using two studies in the GCC specifically we calculate a range of 113–311 kg CO₂/per/yr, which could be captured by 30% or less of a small parcel's canopy as per this study. Lastly, because work is being done to enact similar sustainable transitions along the entire supply-chain for housing manufacturing, transportation infrastructure, and industry in general [135–140], the authors assume future reductions in EC will

roughly mirror the projected reductions in OC posed by this paper. Therefore, the high-level conclusions from this study hold in the long-run, though different transition rates for EC and OC should be considered.

3. The conversion of expanses of desert landscape to low-density, vegetated neighborhoods is a key aspect of this study which does not apply equally to all regions, especially those with constrained land-supply or naturally forested landscapes. Additionally, consideration for limits in raw material supplies (especially rare-earth metals) required for road, car, housing, battery, and solar-PV production is needed. Historically, lower density housing has required more material per-person than higher density alternatives, though the impact of this difference can be mitigated in the future through material substitution and improved efficiencies arising from autonomous vehicle adoption and smaller house design, among others.
4. This paper assumes that driving behavior will remain constant into the future. However, the simultaneous adoption of both electric vehicles (EV) and autonomous driving (AD) may increase the distance driven per family member or lower the average occupancy rate. Both would increase per-person energy demands and emissions, which accounts for 7–29% of total household emissions in this study. Because there is not yet clear agreement on the projected impacts of either EV or AD technologies on future driving behavior [141–144], the authors held current driving behaviors constant for all scenarios.
5. This paper uses averaged climatic data from the preceding decade to run building energy results. A recent study by Radhi [145] concludes that global warming in the region [146] could increase energy demands for cooling by 5–24%. If similar results applied to this study, roof and ground areas required for solar-PV energy production would increase, as would the number of trees required for sequestration. These potential changes to land-use ratios and emissions should be considered when considering the applicability of this paper's results.
6. The phasing of technology, tree planting, and house construction with solar-PV deployment must be considered further before these findings can be applied. For example, trees planted for sequestration in Abu Dhabi, which require 20 years to reach maturity, would be limited by the supply of recycled water until desalination plants transition to solar-PV powered RO. Lowering the EC from house construction supply chains (see above) is another factor that must be considered when optimizing the net carbon of new neighborhood construction in the near term (before supply chains have fully decarbonized) to avoid the carbon spike resulting from new house construction as much as possible [147]. Lastly, once desalination has fully transitioned, laying out neighborhoods and planting trees in advance of projected housing demand would allow trees to reach maturity and full sequestration rates before houses began operating. In desert regions trees could also be used for low-carbon construction materials.

5.2. Future studies

While this research outlines the potential impacts of various sectors on efforts for reducing carbon emissions, several next steps can increase the robustness and implementation potential of the findings. These include:

- Further investigation of the negative environmental impacts of salt-water desalination, especially its saline discharge on sensitive coastal eco-systems.
- A study of cooling energy reduction through natural ventilation

strategies, and microclimatic impacts, on humidity and temperature due to dense tree vegetation.

- Detailed simulation of energy supply-demand balancing with load-shifting and curtailing using household and automobile battery systems to test for off-grid operation [148].
- Planting and tree maintenance strategies and phasing plans (see above) to ensure maximum tree growth and carbon sequestration while avoiding soil and ecosystem disruption, as well as roof-top solar system energy losses from shading.
- Design and user-testing of smaller sized villas for Emirati families that retain cultural and social appropriateness and acceptance.
- A context-specific cost benefit analysis of suburban trees to improve upon the results used from Western studies.
- A complete LCA study for housing, appliances, battery systems, and electric cars under conditions of maximum electrification supplied by solar-PV to allow sizing of sequestration for both operational and embodied emissions (see 5.1 Points 1 and 2). The potential to shift housing construction in the region to wood or other more sustainable materials should also be considered.
- Study to refine ranges of behavioral parameters for daily driving, water use, lighting and equipment use, would further strengthen the conclusions made through the sensitivity analysis (see 5.6).

5.3. Tree sequestration and future landscape design

As research has shown, there are benefits to localizing carbon sequestration programs as opposed to global offset markets [149]. An important aspect of this study is the region-specific application of the widely used tree carbon offset metric [150]. Such an approach allows households, landscape architects, and government planning agencies a nuanced and systematic understanding of the relationship between carbon emissions and sequestration potential resulting from tree planting in low-density housing neighborhoods. It also provides a clear understanding of the significant barrier to bringing the existing water-energy nexus to carbon neutrality, as well as a prompt for rethinking vegetation in Abu Dhabi if and when the water-energy nexus transitions to solar-powered RO.

Due to the historically high carbon emissions resulting from desalination, the role of vegetation in Abu Dhabi has been minimized to be mostly ornamental with emphasis on selective shade trees in public spaces [151]. If trees become carbon negative, it would allow for a reversal in societal attitude and revision of landscape design principles towards increased, even maximum tree planting. This change in attitude would include consideration of other benefits that trees could provide in the Emirati neighborhood context such as increased privacy, increased walkability, noise reduction, improved air quality, microclimatic cooling, house cooling energy demand reduction from shading, and increased property values from improved aesthetics, among others [152–154]. Additionally, if outdoor spaces are cooler and more habitable throughout the year, families may prefer smaller houses for both financial and sustainability reasons. Ultimately, single-family home ownership and the resulting control of landscaping allows households to calibrate the best combination of house size, solar-PV system, tree planting, and technology driven efficiency for their specific budget and lifestyle. The potential financial benefits of owning roof-top solar-plus-battery systems, and the increased resilience to grid outages, is a final advantage of single-family home ownership [155,156].

5.4. Technology costs and barriers to adoption

It is probable that no financial barriers will exist in the near-term that would prevent transitioning to the technologies and house designs required to achieve near-zero carbon operational emissions. While a detailed cost analysis of the proposed transitions is outside the scope of this study, recent studies project that electric cars [157], RO desalination [158], electricity from solar-PV plus storage [44,159], and the net

cost of trees watered from RO water [160], will all have lower lifetime costs than current baseline technologies (Appendix E). Additionally, while building to Passive House standards carries higher up-front cost, these can be recouped through lower operating costs or offset by building a smaller house [161]. It is possible, therefore, that households building new homes and buying new cars in the coming decades will pay less than they would now, while simultaneously achieving near-zero or even carbon neutrality for operational emissions.

5.5. Current Estidama regulations + future government focus

Results from this study show that Estidama's current regulations are stringent enough to achieve net-carbon zero household operations under a fully renewable energy regime (S3 ...). Though these scenarios require additional ground-mounted solar panels to cover all energy needs, the resulting carbon emissions can be reasonably offset by trees planted within parcel and neighborhood open spaces (Fig. 4).⁷ The key missing parameter is SRO desalination. Without SRO powered by solar-PV (or similar renewable), a household's indoor potable water use alone would result in yearly emissions of ~8000 kg CO₂. SRO desalination is a feasible option in the region assuming fouling issues and saline discharge impacts are adequately addressed. While raising Estidama's minimum insulation and efficiency standards in the future would help ensure a path to a low-carbon society, this study shows the more critical effort is towards transitioning from MSF to SRO desalination. Without a full transition, which is currently underway, Abu Dhabi will not be able to achieve carbon neutrality without a significant, and likely very costly, carbon sequestration program.

5.6. Sensitivity to uncertainty

Results from the sensitivity analysis for scenario S6 (Table 6) provides a more nuanced understanding of the likelihood of achieving near zero-carbon OC and the relative importance of individual parameters. Foremost is the need to fully transition to renewable (solar-PV) energy sources and processes (gas to electric car, grid to solar-PV energy, MSF to SRO desalination) (20–160 kg CO₂/%). Presently, besides desalination, households can directly control these energy and technology transitions. If desalination plants transition slowly, households can look to internal water treatment and recycling options [162,163]. Considering the outsized impact of energy source on final OC for S6, energy efficiency measures are most critical for their ability to lower aggregate energy demands below what can be provided for by roof-top solar-PV and grid supplied renewable energy. Of the behavioral factors which have a strong or moderate impact on OC (50–2 kg CO₂/%) most are “lumpy”, long-term decisions which households need to make only every few years or decades. This includes car type, house size, air-conditioning system, and solar-panel type. On the other hand, many day-to-day habits, which can be harder to change, control less important parameters such as car use, indoor water use, window shading (drawing blinds), and lighting and equipment use (1.5–0.1 kg CO₂/%). Cooling set-point has the highest sensitivity of non-transitional technologies and thus smart-thermostats which dynamically balance comfort and efficiency provide a low-cost way to lower OC. Insulation values and air-tightness have less sensitivity (0.3 kg CO₂/%) than might be expected due to the dampening effect of the high COP air-conditioner in S6. This strengthens our argument that Passive House standards are not necessary to achieve near zero-carbon operation, and explains why they may be counter-productive when considering full life-cycle emissions (see 5.1 point 2). House design, as it relates to area per person, remains a critical parameter in relative and absolute terms

⁷ Of course additional solar could be supplied by utility scale installations, but calculating the potential for household or neighborhood scale energy autonomy has additional benefits beyond just carbon neutrality.

due to its direct influence on per-person cooling energy requirements. Lastly, consideration needs to be made for car occupancy rates (1.8 kg CO₂/%) when and if households adopt autonomous mobility to ensure that ‘empty miles’ and rebound effects are kept to a minimum [164]. Overall, the sensitivity analysis suggests that the upfront selection of a modestly sized, efficient home with a few key technology systems is far more important than the family's behavior inside it. That said, cumulatively, behavioral parameters could drive OC beyond what could be captured by on-site vegetation.

6. Conclusions

It has become a common narrative within the urban planning and design disciplines that low-density, suburban development is less sustainable than denser, urban configurations due to increased automobile use and higher household energy consumption. Recent studies have shown that this is not always the case [74,165,166]. Furthermore, the results from this study show that future household emissions can be lowered by a significant enough margin to be fully offset by trees planted at the parcel or neighborhood scale. In the GCC region, and in many other parts of the world, the preferred form of development has been that of lower-density neighborhoods. This study assumes that the strong cultural preference for the villa typology will continue in the region. Based on this assumption, this study provides recommendations that will, in the future, allow less-dense neighborhoods to lower per-person net household operational emissions through technological transitions, housing design improvements, and significant areas of tree planting.

Looking towards such a future, this study shows a clear path to near-zero and even net-carbon neutrality for future household energy use (building energy, water desalination and heating, automobile use) when the following conditions obtain:

- Electrification of desalination through replacement of existing MSF plants with RO desalination plants
- Electrification and increased efficiency of personal transport through replacement of gasoline powered cars with plug-in electric vehicles
- Adoption of roof-top and utility scale solar-PV systems with enough power capacity to serve all direct and indirect operational energy needs (building, desalination, driving)

Without these combined transitions it is not possible for efficiency gains and behavioral changes alone to reduce carbon emissions enough to be offset by household/neighborhood scale afforestation. Nevertheless, these technological transitions are projected to happen through natural replacement of older technologies in the coming decades due to their life-cycle cost benefits in many categories (see Appendix E) [167,168].

Normally sized parcels in Emirati neighborhoods provide between 760 and 1800 m² of open-space which could be used for tree planting. Assuming the above-mentioned technological transitions, existing building construction and appliance standards set by Estidama Pearl 1 regulations provides adequate energy and water efficiency to achieve net-carbon zero operations with a required offset of roughly 30 trees or

~1200 m² of tree canopy. Building to Passive House standards and installing currently available best-in-class appliances further reduces the number of trees required for carbon offsetting to 15 or ~590 m² of tree canopy. Future improvements to solar and desalination technologies could allow all operational carbon emissions from the household to be sequestered by 4–5 trees or ~180 m² of tree canopy.

In all technology scenarios, our model shows that improvements to architectural and landscape design consistently reduce per-person building energy use by 50–60%, which translates to a final per-person carbon emissions reduction of 30–40%. This emphasizes the importance of the allied design professions in fine-tuning the built and landscaped environment to reduce carbon emissions and maximize carbon sequestration. In the future, whether a household is carbon positive, carbon neutral, or carbon negative for operational energy use may very well depend on key design decisions made at the neighborhood, parcel, and building design scales. It has long been argued that small, well-shaded houses are more energy efficient and thus more sustainable. Our research shows that these axioms will remain valid throughout the transition to low-carbon futures [169,170]. Even in a world with zero-carbon energy sources, reducing energy use through good design will reduce the amount of materials required for solar, wind, and battery storage. This is especially important for lower density housing which can have higher per-person material needs than higher density housing. The need to plan for the eventual performative coupling between the built environment and technological systems discussed in this paper puts an increased importance on phasing and land-use planning within the urban design and planning professions. More broadly speaking, our research shows the benefit of multi-scalar, multi-disciplinary projective research and design which integrates approaches from the fields of urban metabolism, urban design, landscape design, architecture and engineering towards developing sustainable housing solutions.

Declarations of interest

None.

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Appendix A

Scenario Input Parameter Values with References.

Model Input Parameters		Units	Scenarios							
			S1	S2	S3	S4	S5	S6	SS1	SS2
Demographics + House Shell Design										
Average Family Size	persons	7	—	[a]	—	—	—	—	—	—
Children (under 18)	persons	3 [91]	—	—	—	—	—	—	—	—
Occupancy Density	m ² /per	75	75	50	75	50	75	50	75	40
House Dimensions	m (w x l)	13.3 × 19.7	10.9 × 16.1	13.3 × 19.7	10.9 × 16.1	13.3 × 19.7	10.9 × 16.1	13.3 × 19.7	13.3 × 19.7	9.7 × 14.5
Floor-to-Floor Height	m	3	—	—	—	—	—	—	—	—
North Window-to-Wall Ratio	%	19.5	26	19.5	26	19.5	26	19.5	19.5	26
East Window-to-Wall Ratio	%	19.5	7.5	19.5	7.5	19.5	7.5	19.5	19.5	7.5
South Window-to-Wall Ratio	%	19.5	16	19.5	16	19.5	16	19.5	19.5	16
West Window-to-Wall Ratio	%	19.5	7.5	19.5	7.5	19.5	7.5	19.5	19.5	7.5
Aggregate Window-to-Floor Ratio	%	15 [39]	10 [d]	15	10	15	10	15	15	10
Window Shading	NA	None	—	—	—	—	—	—	None	Auto-Blinds [d]
[a] Blank cells have same value as cell to its left [c] Maintains minimum of 8% set by International Building Code [d] 5 cm with 3 cm gap – triggered at 250 w/m incidence.										
Solar PV System + Battery Storage										
Roof Surface Panel Coverage	%	—	—	—	85 [a]	—	—	—	—	—
Module Efficiency	%	—	—	—	18 [171]	—	—	—	—	21 [67]
Module Temperature Coefficient	%/C	—	—	—	- 0.28 [171]	—	—	—	—	—
Mounting Type		—	—	—	Open-rack	—	—	—	—	—
Battery Lifecycle	years	—	—	—	15 [b]	—	—	—	—	—
Household Fixed Battery Capacity	kWh	—	—	—	40.5 [c]	—	—	—	—	—
Embodied Carbon Factor (manufacturing)	g CO ₂ /kWh	—	—	—	30 [98]	—	—	—	—	—
Battery Manufacturing Energy Intensity	MJ/kWh	—	—	—	587 [97]	—	—	—	—	—
Carbon emissions for storage	kg/hh/yr	—	—	—	14.5 [d]	—	—	—	—	—
[a] Coverage calculated using First Solar Series 6 panel, 5 cm gap, 5° tilt [b] Author assumption [c] Calculated using Tesla's online estimator [d] Author calculations.										
Building Energy										
Family Occupancy Schedule										
Plug Loads	w/m ²	6 [b]	—	—	—	—	—	—	6	—
Lighting Load	w/m ²	11.1 [e]	—	—	—	—	—	—	11.1 [e]	—
Infiltration Model		change/hr	—	—	—	—	—	—	change/hr	—
Infiltration Rate		0.35 [g]	—	—	—	—	—	—	0.35	—
Cooling Setpoint	C	22 [h]	24 [i]	22	24	22	24	22	22	24
Air-Conditioner Type		VRF	—	—	—	—	—	—	—	—
Air-Conditioner Efficiency	COP	3.4 [g]	—	—	—	—	—	—	3.4	4.5
Maximum Humidity Level	%	50 [g]	—	—	—	—	—	—	50	60
Wall U Value	w/m ² /K	0.32 [g]	—	—	—	—	—	—	0.32	0.09
Roof U Value	w/m ² /K	0.14 [g]	—	—	—	—	—	—	0.14	0.09
Slab U Value	w/m ² /K	0.15 [g]	—	—	—	—	—	—	0.15	0.09
Window U Value	w/m ² /K	2.2 [g]	—	—	—	—	—	—	2.2	0.8
Solar Heat Gain Coefficient	%	0.4 [g]	—	—	—	—	—	—	0.4	0.3

[a] Occupancy data not available for Abu Dhabi families, use ASHRAE 90.1–2013 Prototype Mid-rise Apartment Schedule [b] Estidama only sets appliance efficiency standards so we use (Grondzik et al., 2009) to set a value of 6 w/m² [d] Assume future 25% reduction [e] Estidama average for all room types [f] Assume 200 lumen per watt efficiency and 300 lux/meter light level ("Dubai Lamp, Philips Lighting" 2018) [g] Estidama Pearl 1 Standard [h] ASHRAE Standards 55–2013 [i] Below upper limit of 27 °C set by ASHRAE 55–2013 [j] Trane Water-Source VRF [l] ASHRAE 62.1–2016.

Indoor Water Use	S1	S2	S3	S4	S5	S6	SS1	SS2
Clotheswasher Efficiency	l/use	65 [a]	–	–	50 [b]	–	65	50
Clotheswasher Use Rate	loads/hh/dy	0.34 [56]	–	–	–	–	–	–
Dishwasher Present in House	boolean	No	–	–	Yes	–	No	Yes
Dishwasher Efficiency	l/use	13.2 [a]	–	–	9.1 [c]	–	13.2	9.1
Dishwasher Use Rate	loads/hh/dy	0.6 [56]	–	–	–	–	–	–
Faucet Flow Rate	l/min	6 [d]	–	–	1.8 [e]	–	6	1.8
Average Faucet Event Length	min/event	0.65 [56]	–	–	–	–	–	–
Faucet Use Rate (no dishwasher present)	use/per/dy	26 [56]	–	–	–	–	–	–
Faucet Use Rate (dishwasher present)	use/per/dy	19 [56][f]	–	–	–	–	–	–
Shower Flow Rate	l/min	9.5 [d]	–	–	2.85 [g]	–	9.5	2.85
Shower Use Rate	use/per/dy	6.0 [56]	–	–	–	–	–	–
Toilet Efficiency	l/flush	6.0 [d]	–	–	3.0 [h]	–	6	3.0
Toilet Use Per Day	use/per/dy	5.7 [56]	–	–	–	–	–	–
Water Leak Rate	%	7 [173] [i]	–	–	1 [173] [j]	–	7	1
Distribution Losses	%	10 [174]	–	–	–	–	–	–
Hot-Water Heater Efficiency	factor	0.9 [k]	–	–	4.5 [l]	–	0.9	4.5
Percent Desal from Reverse-Osmosis	%	0	100	–	–	–	–	–
Percent Desal from Multi-Stage Flash	%	100	0	–	–	–	–	–

[a] No Estidama standard, use value from ("Abu Dhabi Residential End Use Study Extract" 2013) [b] 50 L a cycle with an IWF of 3.2 (<https://www.energystar.gov>). [c] Bosch 800 Series, Program 6 Cycle (www.bosch-home.com) [d] Estidama Pearl 1 Standard [e] Average of low and high flow, Altered: Nozzle Dual Flow (www.alteredcompany.com) [f] Reduction of faucet use calculated from (Stamminger et al., 2007) [g] Nebia Spa Shower (www.nebia.com) [h] Niagara Corporation, Stealth line (www.niagracorp.com/stealth) [i] Average leak-rate and [j] Median leak-rate [k] Typical electric resistance [l] Sanden Eco-Plus Model GUS-A45HPA (www.sandenwaterheater.com).

Transportation	min/day	55 [a]	–	–	–	–	–	–
Average Travel Time	km/hr	35 [55][b]	–	–	–	–	–	–
Average Travel Speed	km/per/dy	31.5	–	–	–	–	–	–
Average Car Occupancy	per/car	1.55 [55] [c]	–	–	–	–	–	–
"Good" Car Efficiency in Abu Dhabi	l/100 km	7.35 [d]	–	–	–	–	–	–
Electric Car Efficiency	kWh/100 km	NA	–	–	–	–	–	–
Percent Travel Gas Car	%	100	23.0 [e]	–	15.4 [f]	–	–	–
Percent Travel Electric Car	%	0	0	–	–	–	–	–
Percent Travel Electric Car	%	0	100	–	–	–	–	–
[a] Assume (1) 90min, (3) 60min, and (3) 30min travelers per day based on demographics, [b] Conservatively assume fastest suburban travel speed of 35 km/h ("Abu Dhabi Travel Patterns: Highlights of the 2009 Survey Results." 2012) [c] No data available for Abu Dhabi, use U.S. personal vehicle occupancy rate as proxy [d] From Abu Dhabi government (EMS. n.d. 2018) [e] Tesla X (www.fueleconomy.gov); [f] Hyundai IONIQ (www.fueleconomy.gov).								

Energy (EF) and Carbon Factors (CF)	kWh/m ³ /km	0.007 [81]	–	–	–	–	–	–
EF for Water Conveyance	km	60 [a]	–	–	–	–	–	–
Desalination Conveyance Distance	kWh/m ³	4 [110]	–	–	–	–	–	2 [70]
EF for Reverse Osmosis Desalination	kWh/m ³	18 [43]	–	–	–	–	–	–
EF for MSF Desal in kWh equivalent	kWh/l	8.8	–	–	–	–	–	–
EF from Gasoline in kWh equivalent	kg/kWh	0.011 [41,93]	–	–	–	–	0.006 [42]	–
CF for Solar PV Electricity		–	–	–	–	–	–	–

CF for Abu Dhabi Grid Electricity	kg/kWh	0.47 [43]	—	—	—	—
CF for MSF Cogeneration Desalination	kg/m ³	12.79 [43]	—	—	—	—
CF for Gasoline Car Use	kg CO ₂ /l	2.35 [b]	—	—	—	—
Average Carbon Sequestration Per Tree	kg/tree/yr	—	—	—	—	—
Average Carbon Sequestration Per Canopy	kg/m ² /yr	—	—	—	—	—
		39.3 [c]	—	—	—	—
		0.95 [c]	—	—	—	—

[a] Author measure from Taleewah desalination station to Al Shamkha development [b] <https://www.epa.gov> [c] Appendix B.

Appendix B

Tree Allometry, Water Use, and Net Sequestration.

Tree Species		Tree Allometry			Water Needs		Net Sequestration (kg CO ₂ /yr)		
Latin Name	Common Name	Age	Height	Crown Diameter	Species Coefficient [a]	Watering Needs Per Tree [b]	Gross Emissions Per Tree [c]	Net Emissions Per Tree [d]	Net Emissions Per m ² Canopy Area
		year	m	m		m ³ /yr			
<i>Prosopis cineraria</i> <i>Morus alba</i>	Ghaf Tree	20.0	9.6	8.3	0.3	45.5	2.2	-102.9	- 1.90
	White Mulberry	20.0	8.5	8.4	0.5	78.5	3.8	- 61.2	- 1.09
<i>Parkinsonia aculeata</i>	Jerusalem Thorn	20.0	7.3	6.4	0.2	17.9	0.9	- 47.8	- 1.49
<i>Casuarina</i>	Ironwood	20.0	9.6	8.3	0.3	45.6	2.2	- 39.8	- 0.74
<i>equisetifolia</i> <i>Delonix regia</i>	Royal Poinciana	20.0	5.4	7.1	0.2	22.0	1.1	- 29.7	- 0.76
<i>Calophyllum</i>	Kamani	20.0	7.1	6.0	0.5	39.2	1.9	- 28.1	- 1.01
<i>inophyllum</i> <i>Olea europaea</i>	Olive	20.0	6.7	6.8	0.2	20.2	1.0	- 21.9	- 0.61
	Carrotwood	20.0	7.6	7.2	0.5	56.3	2.7	- 15.8	- 0.39
<i>Cupaniopsis</i> <i>anacardioides</i> <i>Phoenix Dactylifera</i>	Date Palm	20.0	7.1	3.7	0.5	14.9	0.7	- 6.0	- 0.56
Median			7.3	7.1	0.3	39.2	1.9	- 29.7	- 0.76
Average			7.7	6.9	0.4	37.8	1.8	- 39.3	- 0.95
Avg. Four Worst Species			7.1	5.9	0.4	32.6	1.6	- 18.0	- 0.64
Avg. Four Best Species			8.8	7.9	0.3	46.9	2.3	- 62.9	- 1.31

[a] L = 0.2, M = 0.3, M = 0.5, M + = 0.7, H = 0.8 [b] Reference Eto = 2437 mm/year; 15% water volume added to account for delivery losses [c] Assumes water comes from RO desalination at 4.4 kWh/m³, and powered by solar panels with carbon factor of 11 g/kWh [d] Net emissions = gross emissions – tree sequestration.

Appendix C

Energy Use By Scenario and Category (kWh-e/per/yr).

Scenario	Building Energy			Water			Driving		Total
	Cooling	Lighting	Equipment	Total	Desalination	Hot-Water	Total	Total	
Existing Villa									
S1 (T1-D1)	9044	2396	2595	26,175	2538	384	2922	5393	34,490
S2 (T1-D2)	4127	1597	1730	14,035	1674	255	1929	4799	20,763
S3 (T2-D1)	9044	2396	2595	7454	1674	255	1929	4799	14,181
S4 (T2-D2)	4127	1597	1730	14,036	409	255	664	1706	16,406
S5 (T3-D1)	4056	324	1687	7454	409	255	664	1706	9824
S6 (T3-D2)	2209	215	1125	6067	110	155	265	1143	7474
SS1	9044	2397	2595	3549	110	155	265	1143	4956
SS2	1737	173	668	14,036	409	255	664	1143	15,842
				2578	60	133	193	1143	3914

Appendix D

Household Energy Balance [a].

Scenario	Energy Demands (MWh-e/hh/yr) [b]			Energy Supply (MWh-e/hh/yr)					Additional PV Sizing		
	Household Operational Energy	Desalination for Tree Watering	Total Household Energy Demand	% of S1	Gasoline	Natural Gas	Grid Elec.	Roof PV System	Additional PV Required	Additional PV Area Per Family (m ²)[b]	% of Medium Large Parcel
Existing Villa	241.4	1017.2	241.4	166%	37.8	17.8	185.9				
S1 (T1-D1)	145.3	594.4	145.3	100%	33.6	11.7	100.0				
S2 (T1-D2)	99.3	394.4	99.3	68%	33.6	11.7	54.0				
S3 (T2-D1)	114.8	5.7	120.6	83%				62.6	58.0	221.2	29%
S4 (T2-D2)	68.8	3.5	72.2	50%				41.7	30.5	116.4	15%
S5 (T3-D1)	52.3	2.7	55.0	38%				62.6	0.0		6%
S6 (T3-D2)	34.7	1.8	36.5	25%				41.7	0.0		
SS1	110.9	3.1	113.9	78%				73.1	40.9	156.1	21%
SS2	27.4	0.4	27.8	19%				39.0	0.0		9%

Note: Grayed numbers show energy required to desalinate water from a hypothetical Solar-RO system to support necessary trees for sequestration. It is provided for illustrative purposes only. [a] Household = 7 persons [b] For detailed breakdown of energy use by category see Appendix C [c] Assumes 85% panel coverage of ground mounted or other solar installation.

Appendix E

Cost of Advanced Technologies Relative to Current Baseline Technologies.

	Relative Costs to Current Technologies		Comments
	2018	2030–2040	
System Electric Car	Even to Lower	Much Lower	Current electric cars are cost competitive, if not already cheaper. Future electric cars predicted to be far cheaper to own and operate [118,157,175].
Passive House Standards	Higher	Higher to Even	Passive House standards between 5 and 15% more expensive up front, with pay-back periods depending on energy costs. Smaller house design can offset higher construction costs. Low-Energy construction standards, somewhere between Estidama and Passive House standards are likely only 5% added costs [161,176–179].
RO Desalination	Lower	Much Lower	RO costs in Abu Dhabi are already significantly cheaper than thermal cogeneration, relative costs will only improve in future as RO becomes cheaper and natural gas prices increase [109,158,180].
Solar PV + Battery	Even to Lower	Much Lower	Utility scale and estimated roof-top solar already cheaper than unsubsidized cogeneration (2.5, 7, and 9 cents respectively), offsetting battery cost*. Rapid battery and solar improvements should make systems much cheaper in the future [44,45,159].
Tree With RO	Even to Slightly Higher	Even to Lower	RO costs projected between \$1.50 to \$0.50 in the near future [a]. Average tree from Appendix B would cost between \$19–\$57 to water per year. Net cost benefits of trees in United States context estimated at \$55 - \$107 for medium to large trees (in 2018 dollar). Additional watering costs in Abu Dhabi likely produces break-even or slight cost benefit in near future [160,181–183].

* Assumes: 3 T Power Walls (\$17,200), \$0.07 roof-top solar cost, \$0.09 grid cost (to government), 70,000 kWh/hh/year. Electricity savings = \$1400/yr or \$21,000 over 15 yr battery lifetime.

Appendix F

Estimated Embodied Carbon Emissions.

Embodied Carbon Studies	Embodied Energy [a]		CO ₂ Factor [b]		Embodied Carbon		Housing Area [c]		Emissions Per-Person		Canopy Area Required to Offset	
	MJ/m ² /yr		kg CO ₂ /MJ		kg CO ₂ /m ² /yr		m ² /per		kg CO ₂ /per/yr		m ²	
	Low	High	Low	High	Low	High	Low	High	Low	High	Low	High
Low-Energy Range (Review) [133,184]	11.5	330	0.06	0.06	0.69	227.7	50	50	35	11,385	26	17,789
Passive House Range (Review) [133,184]	16.5	471	0.06	0.06	0.99	466.29	50	50	50	23,315	38	36,429
Passive Study [147]	-	-	-	-	17.6	-	50	50	880	-	672	1375
Low-Energy Study [124]	-	-	-	-	11	-	50	50	550	-	420	859
Kuwait Low-Energy Villa Study [122]	-	-	-	-	2.25	4.2	50	50	113	210	86	328
Saudi Arabi Typical Villa Study [185]	103.7	-	0.06	-	6.2	-	50	50	311	-	237	486

[a] Normalized to 100 year lifespan [b] Multiplier taken from Stephan et al., 2013 [c] Value from smaller house design in this study.

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