Energy, Water, and Food Nexus Simulation for Built Environments in a Desert Climate

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Abstract

This paper presents a comprehensive framework that explores the integration of building-integrated agriculture (BIA) in residential buildings located in desert climates, focusing on the synergies and dependencies between energy, water, and food systems. The methodology involves modeling a typical single-family household, incorporating systems such as water reuse, photovoltaics, and a hydroponic farm, and evaluating key performance indicators (KPIs), including energy consumption, water consumption, food production, and CO₂e emissions. The results demonstrate that BIA can fulfill the food demands of multiple households while reducing carbon emissions, with the inclusion of photovoltaic panels further mitigating energy consumption. Greywater reuse contributes to water conservation, and the overall CO₂e emissions are significantly reduced. These findings highlight the potential of resource-efficient systems to improve sustainability and resilience in desert regions, providing valuable insights for stakeholders and researchers.

Key innovations

- Develops a framework to identify synergies and dependencies between energy, water, and food systems in the built environment, focusing on residential buildings in a desert climate in Saudi Arabia.
- Proposes a bottom-up methodology that showcases the potential for adopting resource-efficient systems to enhance a region’s resiliency given growing populations and rapid urbanization.
- Offers insights and recommendations for policymakers, practitioners, and researchers to enhance the sustainability and resilience of residential buildings in desert climates.

Practical implications

Currently, no simulation tool can holistically simulate buildings’ energy, water, and food systems. This paper develops a framework to holistically evaluate the three systems on a building scale, using Honeybee Energy tools to simulate energy and manual calculation for water and food. Then, it will be assessed holistically using the CO₂ equivalent as the unified metric.

Introduction

Energy, water, and food are critical resources for human survival; the interdependencies between these systems, also known as the “nexus”, passed through multiple stages to gain global recognition. Firstly when presented in Bonn2011 Nexus Conference: The Water, Energy and Food Security Nexus (Hoff (2011)), then In 2012, it was addressed at the Rio+20 Summit (UN (2012)); furthermore, the task force on the Water-Food-Energy Ecosystems was created in 2013 by the United Nations Economic Commission for Europe (UNECE (2021)).

Buildings consume 40% of the total energy produced (Tricoire (2021)) and 30% of the available freshwater globally (Ferriz-Papi (2012)); they also contribute to 33% of greenhouse gas emissions (Tricoire (2021)). In the food sector, agriculture globally consumes around 60% of freshwater withdrawals, takes up to 40% of the land surface, and produces 17 to 32% of greenhouse gas emissions (Bellarby (2008)). For example, in the US, which has one of the world’s most advanced infrastructures, food is estimated to travel 1500 miles (2400 km) to reach the end consumers (Hill (2008)). Due to these issues, Building-Integrated Agriculture (BIA) was introduced, and it utilizes unused rooftops and facades for agricultural purposes. BIA will lower the carbon footprint, diminish transportation costs due to end-user proximity, improve food security and safety, and cool down buildings (Gould (2012)).

Desert climates specifically face major vulnerabilities, mainly water scarcity (Yegorov (2015)) and domestic food production (Benis (2018)), thus can benefit from utilizing BIA. Deserts occupy approximately one-fifth (20%) of the earth’s land area, and more than one billion people live in this climate (Nunez, 2020). This paper investigates the literature in the energy, water, and food nexus domain and identifies the gap to be in the building scale analysis, specifically in a desert climate.

The nexus between energy, water, and food in buildings emerged primarily with the introduction of BIA. Valencia (2022) shows that integrating food production in a building with renewable energy systems (e.g., Photovoltaics) and greywater reuse and rainwater harvesting presented an opportunity to design the three systems in an integrated manner to optimize them together. In addition, the use of such systems increases the resilience of the built environment in terms of food security, energy, and water relia-
bility. Also, the carbon footprint of these systems (specifying the CO\textsubscript{2} equivalent of each system) was used as a unified metric to evaluate the systems as a whole; a system dynamics model was used to assess the three systems (Valencia (2022)). Multiple models have been applied to model and evaluate the interconnections between the three systems on an urban scale (Ferroukhi (2015); Dagher (2015); Purwanto (2019)), but only a few models have been used/developed to evaluate the systems or plan for them on a building scale.

Jones (2022) identifies the barriers preventing collaborative governance of the nexus in Phoenix, Arizona (Jones (2022)). Phoenix has a climate that is close to the Middle East, but the study tackles collaboration on a city level for the urban-scale development of these systems, no part of it discussed the nexus on a building scale. Multiple case studies in the middle east analyzing the nexus on an urban scale have been documented (Rambo (2017); Okonkwo (2021)). None of the reviewed literature has evaluated the nexus on a building scale in a desert climate.

The Pasona Urban Farm in Tokyo, Japan, is an interesting success story of a building utilizing all three systems in an optimized manner. It is a nine-story office building that allows users to produce their own food at work. It was built in 2010. It has approximately 200 different types of crops and is outfitted with energy-saving lighting and innovative irrigation technology. It features a green double-skin facade that serves both aesthetic and functional purposes; it improves the building’s insulation, lowers energy consumption, and elevates food yields. (Andrews (2013)).

**Methodology**

The goal is to identify the synergies and codependences between the energy, water, and food nexus on a building scale and develop a framework that enhances these synergies to save water and increase domestic food production while lowering the CO\textsubscript{2} equivalent. To achieve this, an experimental design (Figure 1) has been developed as follows:

**Model Setup**

The first step is to identify the Key Performance Indices (KPIs) from the literature, which are: energy consumption (EUI), water consumption (m\textsuperscript{3}), food production (kg), and CO\textsubscript{2} equivalent (kg). Then specify the archetype to be studied. For this study, the residential archetype has been specified.

Then creating the 3D model in Rhino utilizing the Saudi Building Code (SBC) and typical buildings in the region, then adding the required systems (water reuse, Photovoltaics, and a hydroponic farm) into the model, as well as acquiring the weather file for Riyadh to be inputted in the model and creating specific thermal zones depending on the set-points of the building and the BIA.

**Simulation**

Analyzing the model to determine the performance metrics using Honeybee energy tools in Grasshopper to analyze the energy performance of the model, and manual calculation utilizing spreadsheets to study the food production, as well as to determine water consumption based on the fixtures in the model and the demand from the BIA, and savings from all three systems, lastly to convert the water and energy consumption and food production into CO\textsubscript{2} equivalent.

**Results**

Visualizing the results based on the simulation outputs and identifying any possible synergies between the systems, then comparing the results with the baseline KPIs to determine if the CO\textsubscript{2} equivalent of the proposed model does not increase but food production is added. In that case, it is added to the study results; if not, the model setup must be revised and edited until the results are met.

**Experimental Setup**

A typical household in Riyadh, Saudi Arabia, has been created using the SBC and typical buildings with a gross built area of 875 m\textsuperscript{2} as shown in Figure 2 with six occupants; the BIA has been added to the household’s rooftop. The crop chosen for this study is tomatoes because it is grown in relatively higher temperatures and has been stud-
ied thoroughly in the region (Benis (2018)).

The specifications and performance metrics of the farms were provided by Freight Farms, a company located in Boston, which re-purposes shipping containers for use as greenhouses (Figure 3).

Results

Energy Analysis

From the literature, the Energy Use Intensity (EUI) for a typical household in Saudi Arabia is 176.50 kWh/m² (Asif (2014)). The distribution of uses between systems has been identified using the Electricity and Water End Use for the Kingdom of Saudi Arabia – Saudi National Water Company (NWC) (Figure 4a).

The energy runs were simulated using HoneyBee Energy tools on the 3D massing, which was done on Rhino. After applying the Saudi Building Code (SBC) specifications for materials and Insulation on the 3D massing, a EUI of 177.36 kWh/m² was found, which has a 0.5% difference from the literature baseline with similar percentages of system uses (Figure 4b).

After adding the BIA, energy use spiked to 269.40 kWh/m², which was expected as the BIA system requires high loads to create the climatic needs for the crops to grow (e.g., lighting, temperature, and other factors), as shown in the table shared by Freight Farms (Figure 4c).

The addition of PV panels on the rooftop of the household to harness solar incident radiation was applied to the model to solve this spike. The output of the PV array was calculated using the National Renewable Energy Laboratory’s (NREL) PVWatts Calculator (NREL (1999)), which shows an output of 90,129 kWh/Year. This translates into a EUI reduction of 99.62 kWh/m², which gives a final EUI value of 169.78 kWh/m², which gives a reduction of 4.3%.

Water Analysis

The baseline for residential household water consumption has been identified by the Water End Use Study for the Kingdom of Saudi Arabia – NWC, which shows that a typical household with six residents (same as the model) has an average water consumption of 136.78 L/Capita. For the purpose of this research, the baseline was used as a reference point, and a spreadsheet was created to map out the water usage from each fixture in the household to identify the amount of greywater and blackwater for water reuse in the BIA and toilet flushing.

The fixtures have been identified by specifying the number of toilets in the household (from the plans) and the types
After calculating the water consumption per Capita was found to be 142.73 L/Capita, which has a marginal increase from the consumption found in the literature. The greywater and blackwater usage breakdown was identified as well. Furthermore, the BIA water demand was specified from the data sets shared by Freight Farms (Farms (2022b)) (Table 1).

<table>
<thead>
<tr>
<th></th>
<th>Greywater (L)</th>
<th>Blackwater (L)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Toilet Flushing (L)</td>
<td>188,544.40</td>
<td>124,041.60</td>
</tr>
<tr>
<td>BIA Demand (L)</td>
<td>54,750</td>
<td>13,816.75</td>
</tr>
</tbody>
</table>

These calculations show that greywater can cover the yearly demand of the BIA and toilet flushing (reducing blackwater usage by 44.14%), ultimately reducing the household’s water usage by 18% (Figure 6).

### Food Analysis

Based on the Food and Agriculture Organization (FAO) data sets (FAO (2013a,b)) for the total tomato production, imports, and exports in Saudi Arabia, the per capita tomato consumption was calculated to be 22.49 kg/yr, subsequently, the total consumption for a typical household was found to be 134.94 kg/yr.

Comparing the household’s total consumption with the yield from the BIA, which is 1,814.37 kg/yr (Farms (2022b)), we can see that 13.45% of the total yield from the BIA covers the demand from the household. This shows that the production from this household can cover the demand for seven other households with the same occupancy level.

The use of hydroponics immensely cuts water usage from agriculture, but as a controlled environment, it would demand high energy loads, as seen in the Energy Analysis section. Furthermore, BIA does not require large areas to produce the same amount as traditional agriculture (Table 2).

### CO₂ Equivalent

CO₂ equivalent is used as a common metric to combine energy, water, and food. To find the CO₂ equivalent for each of them, the Emission Factor (EF) was identified for Electricity (Brander (2011)), water (Benis (2018)), and agriculture (Benis (2018)) as shown in Table 3.

Using the EFs, the total CO₂ equivalent for the baseline and model (with and without PV). The calculations show...
Table 2: Traditional agriculture vs. Hydroponic

<table>
<thead>
<tr>
<th>Type</th>
<th>Water Usage (L/yr)</th>
<th>Energy Usage (kWh/yr)</th>
<th>Land Requirement (m²)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Traditional</td>
<td>188,694.48</td>
<td>1,651.08</td>
<td>307.52</td>
</tr>
<tr>
<td>Hydroponic</td>
<td>13,816.75</td>
<td>88,538.89</td>
<td>29.73</td>
</tr>
</tbody>
</table>

Table 3: Emission Factors

<table>
<thead>
<tr>
<th>Electricity (kgCO₂ eq/kWh)</th>
<th>Water (kgCO₂ eq/L)</th>
<th>Agriculture (kgCO₂ eq/kg)</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.877</td>
<td>0.05</td>
<td>6.314</td>
</tr>
</tbody>
</table>

Discussion

The study highlights the promising potential of building-integrated agriculture (BIA) in desert climates. BIA systems, employing vertical farming, hydroponics, and advanced controls, offer sustainable solutions by addressing food demands, reducing carbon emissions, and conserving energy and water resources. However, challenges such as system management, economic feasibility, and adaptability need to be addressed. Effective control mechanisms, smart building integration, and automated monitoring are essential. Evaluation of costs, revenue streams, and long-term financial viability is crucial. Context-specific adaptation and collaboration among stakeholders are necessary for successful implementation. Overall, BIA has the capacity to revolutionize food production, enhance energy efficiency, and mitigate water scarcity in arid regions.

Conclusion

After applying the framework to a typical single-family household in Riyadh, Saudi Arabia, the simulation has shown an increase in energy consumption compared to the baseline, which was 177.36 kWh/m², due to the addition of the BIA. To mitigate this increase, PV panels were added, ultimately lowering the energy consumption to 169.81 kWh/m² (4.3% Reduction). Also, the water calculation shows that the graywater output (188,544.40 L) of the household covers the demand from the BIA (13,816.75 L) and toilet flushing (54,750 L), which gives us around an 18% reduction in the household’s total water consumption. Furthermore, the BIA has an estimated yield of 1,814.37 kg/yr, while the demand for a typical household with six occupants is 134.94 kg/yr; this shows that 13.45% of the output covers a year’s demand for this household, which highlights that this system can cover multiple households, showcasing that this topic needs further investigation adding more crops and assessing the subsequent effects on the nexus on a larger scale.

Lastly, the CO₂ equivalent decreased by 9.513% from the baseline. Incorporating such a system provided a better method to utilize a household’s water and energy resources to produce food while lowering the CO₂ equivalent; with the current climate problems and risks facing the world, a region’s resiliency is highly connected to its independence in its resources.

Future Studies

While this paper provides valuable insights into the integration of building-integrated agriculture (BIA) in residential buildings in desert climates, there are several avenues for future research to further enhance the understanding and implementation of resource-efficient systems in the built environment. The following future studies can be pursued:
• Scale-Up Analysis: The current study focuses on a single-family household, but future research can explore the scalability of BIA systems in larger residential buildings or at the community level. By analyzing the performance and synergies of BIA in larger contexts, researchers can provide valuable information for urban planners and policymakers in designing sustainable and resilient neighborhoods (Figure 8).

• Techno-Economic Analysis: In addition to evaluating the energy, water, and food aspects, future studies can conduct a comprehensive techno-economic analysis of BIA systems. This analysis should include the cost-benefit analysis, payback period, return on investment, and economic feasibility of implementing BIA in residential buildings. Such information will help stakeholders make informed decisions and incentivize the adoption of resource-efficient systems.

• Lifecycle Assessment: To fully understand the environmental impact of BIA systems, future research can conduct a lifecycle assessment (LCA) that considers the entire life cycle of the building-integrated agriculture, including the production and disposal of materials, construction processes, operational phase, and end-of-life scenarios. LCA can provide a holistic perspective on the sustainability of BIA systems and identify potential areas for improvement.

• Social and Behavioral Factors: It is important to consider the social and behavioral aspects of implementing BIA in residential buildings. Future studies can investigate the acceptance, perception, and adoption of BIA systems among residents. Understanding the attitudes, motivations, and barriers can inform strategies for promoting sustainable behavior and enhancing the social acceptance of resource-efficient systems.

• Climate Change Resilience: Desert regions are particularly vulnerable to the impacts of climate change. Future research can explore how BIA systems in residential buildings can enhance climate change resilience by adapting to changing environmental conditions, such as extreme temperatures, water scarcity, and increased frequency of droughts. Strategies for optimizing BIA systems to cope with climate variability and ensuring food and water security in desert climates should be investigated.

• Policy and Regulatory Frameworks: To facilitate the widespread adoption of BIA in residential buildings, future studies can focus on developing policy and regulatory frameworks that support and incentivize the implementation of resource-efficient systems. Research can analyze the existing policies, identify gaps and barriers, and propose recommendations for creating an enabling environment for BIA integration.

• Integration of Smart Technologies: The integration of smart technologies, such as sensors, automation, and data analytics, can optimize the performance of BIA systems in residential buildings. Future research can explore the potential of smart technologies in monitoring and controlling energy, water, and food systems, improving resource efficiency, and enabling real-time decision-making.

• Long-Term Monitoring and Evaluation: Conducting long-term monitoring and evaluation of BIA systems in residential buildings to assess their performance, identify potential issues or inefficiencies, and gather data for continuous improvement is crucial. Future studies can establish monitoring programs and evaluate BIA systems’ long-term sustainability and resilience under different operating conditions.

By addressing these future research directions, we can further advance the understanding and implementation of building-integrated agriculture in desert climates and contribute to developing sustainable and resilient built environments. The findings from these studies will provide valuable insights for stakeholders, policymakers, and researchers involved in enhancing the sustainability and resilience of residential buildings.

Acknowledgment

We would like to acknowledge Freight Farms for providing valuable data for our research. Their contribution has been instrumental in our work, and we are grateful for their support. Additionally, we would like to thank Yasser El Masri for his help and guidance in the simulation. His expertise has been invaluable, and we appreciate his contributions to our research.

References