# GHG Emissions Reduction – Optimal Design and Operation of the Integrated Distributed Energy Systems Cross Different Energy Sectors

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*Abstract:*

This research seeks the opportunity to further reduce the minimum GHG emissions achieved by individu-ally operating energy systems in the civic, industrial, and transportation sectors through their integration. Each entity – buildings or industrial plants, is equipped with a set of combined cooling, heating, and pow-er (CCHP) system. At the same time, there is heat and electricity transfer among entities. The integration intends to solve the mismatch between the energy demand and energy provided by the CCHP system, which further increases the operation of the CCHP system and reduces GHG emissions of the entire sys-tem. This research introduces an optimization approach for identifying the optimal design and operation of the integrated system, which provides the maximum GHG emission reduction benefits (represented as GHG emissions reduction percentage (GHGD%)). Compared to existing studies on the integrated system, this research (1) differentiates the temperature of industrial heating demands to ensure feasible heat trans-fer; (2) optimizes production rates of plants to minimize GHG emissions of the entire system; (3) identi-fies the optimal relationship between sizes of entities to maximize GHG emissions reduction percentage of the integrated operation. This research implements an integrated system combining entities with different energy demand patterns to balance the supply and demand of heating and electricity. The civic buildings – a residential building and a supermarket that requires more electricity than heating are combined with industrial plants – a confectionery plant, a brewery, and a bakery plant. The confectionery plant and the brewery require more heating than electricity. The bakery plant is investigated under two situations – higher heating than electricity demand and higher electricity demand than heating demand to explore the impacts of changing the energy demand pattern of an entity on GHG emissions reduction benefits of the integrated system. The research also considers the implementation of electric vehicles in the residential building. Results from the case studies indicate that there exist optimal relative entity sizes that lead to a maximum GHGD% of 17.6%. By optimizing the sizes of entities, the highest GHGD% can be maintained at 15.7% - 17.6%, even when the optimal relative entity sizes cannot be followed or there are changes in the energy demand patterns of entities.

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# GHG Emissions Reduction – Optimal Design and Operation of the Integrated Distributed Energy Systems Cross Different Energy Sectors

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## ABSTRACT

This research seeks the opportunity to further reduce the minimum GHG emissions achieved by individually operating energy systems in the civic, industrial, and transportation sectors through their integration. Each entity – buildings or industrial plants, is equipped with a set of combined cooling, heating, and power (CCHP) system. At the same time, there is heat and electricity transfer among entities. The integration intends to solve the mismatch between the energy demand and energy provided by the CCHP system, which further increases the operation of the CCHP system and reduces GHG emissions of the entire system. This research introduces an optimization approach for identifying the optimal design and operation of the integrated system, which provides the maximum GHG emission reduction benefits (represented as GHG emissions reduction percentage (GHGD%)). Compared to existing studies on the integrated system, this research (1) differentiates the temperature of industrial heating demands to ensure feasible heat transfer; (2) optimizes production rates of plants to minimize GHG emissions of the entire system; (3) identifies the optimal relationship between sizes of entities to maximize GHG emissions reduction percentage of the integrated operation. This research implements an integrated system combining entities with different energy demand patterns to balance the supply and demand of heating and electricity. The civic buildings – a residential building and a supermarket that requires more electricity than heating are combined with industrial plants – a confectionery plant, a brewery, and a bakery plant. The confectionery plant and the brewery require more heating than electricity. The bakery plant is investigated under two situations – higher heating than electricity demand and higher electricity demand than heating demand to explore the impacts of changing the energy demand pattern of an entity on GHG emissions reduction benefits of the integrated system. The research also considers the implementation of electric vehicles in the residential building. Results from the case studies indicate that there exist optimal relative entity sizes that lead to a maximum GHGD% of 17.6%. By optimizing the sizes of entities, the highest GHGD% can be maintained at 15.7% - 17.6%, even when the optimal relative entity sizes cannot be followed or there are changes in the energy demand patterns of entities.

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## INTRODUCTION

Current research shows that integrating energy systems across different sectors can reduce greenhouse gas (GHG) emissions and improve the efficiency of the entire system [1]. As a typical distributed energy system, the combined cooling, heating, and power (CCHP) system is an efficient solution for integrating different forms of energy.

The CCHP system generates cooling, heating, and electricity locally by burning fuel in its power generation unit (PGU). With multiple types of energy being generated, the operation of an individual CCHP system is generally limited by the lower energy demand to avoid generating excess energy that cannot be used. Thus, outputs of the CCHP system can be limited, even the systems having high efficiencies. Supplementary equipment is implemented beyond the CCHP system to meet the demands of consumers entirely, which generally includes boilers, solar thermal collectors, photovoltaics [2], and electric chillers [3].

A potential solution for the unbalanced energy demand and supply problem is combining CCHP systems of multiple consumers (entities) to form an integrated energy system. Each entity in the integrated system has its own distributed energy system to generate heating, cooling, and electricity locally. Additionally, it performs both as a consumer and supplier that transfers energy to and receives energy from other entities in the integrated system [4].

This work explores the GHG emission reduction possibility of the integrated system that combines the residential, commercial, industrial, and transportation sectors compared to the individual operating energy systems (the non-integrated system). It addresses the following questions that have not been discussed before: 1. Integrating distributed energy systems of residential, commercial, industrial, and transportation sectors with different energy demand patterns. Temperatures of industrial production processes are differentiated to ensure feasible heat processes. 2. Production rates of the industrial plants are optimized for minimizing GHG emissions of the entire system. 3. Identify the optimal relative entity sizes that maximize GHG emissions reduction benefits of the integrated operation. 4. Explore the impacts of changing the relative entity size and energy demand pattern of entities on GHG emissions reduction of the integrated system.

## OPTIMIZATION PROBLEM FORMULATION

In this work, the GHG emissions reduction benefits of the integrated operation are measured by the GHG emissions reduction percentage (GHGD%). As shown in Eq. (1), it is calculated based on the minimum GHG emissions of the integrated system and the non-integrated system. Therefore, optimization problems have been developed to find the corresponding optimal design and operation of the two systems. The optimal design includes both capacity of each energy system equipment and the size of each entity. The optimal operation contains the amount of energy used and generated by each piece of equipment and the production rates of plants.

$$GHGD\% = \frac{\min GHG_{non-int} - \min GHG_{int}}{\min GHG_{non-int}} \tag{1}$$

### Energy system

### Energy system description

Each entity in both the integrated system and the non-integrated system has been assumed to have options to install the equipment, as shown in Figure 1.

The power generation unit (PGU) has been assumed as an internal combustion engine that generates electricity by burning fuel. An entity can also connect to the external grid to purchase electricity to fully meet the electricity demand, as well as sell electricity back to the grid for credits. The PGU also generates heat along with electricity. After being recovered by the heat recovery unit, the waste heat is used by the absorption chiller for cooling purposes or used by the heating coil for heating purposes. An entity is also able to install a boiler and an electric chiller for heating and cooling, respectively. For the integrated system, an entity can also receive or dispatch electricity and heat from other entities at a specific time. As for entities of the non-integrated system, the heat and electricity transfer among entities are not available.

Electric vehicles (EVs) are formulated as an aggregated subsystem of the residential building to simplify the formulation. It has been assumed that the EVs can both be charged and discharge electricity when connecting to the energy system of the residential building before 8:00 and after 17:00 daily. All EVs must be fully charged before leaving the building each day.

### Decision variables

The amount of heating ($Q_{i,t}^{PGU}$) and electricity ($E_{i,t}^{PGU}$) generated by the PGU are calculated based on its electric efficiency and fuel consumption, as shown in Eqs. (2) and (3).

$$E_{i,t}^{PGU} = \eta_i^{PGU} n_{i,t}^{PGU} \tag{2}$$

$$Q_{i,t}^{PGU} = (1 - \eta_i^{PGU}) \eta_i^{rec} n_{i,t}^{PGU} \tag{3}$$

$\eta_i^{PGU}$ and $\eta_i^{rec}$ stands for electric efficiency of the PGU and efficiency of the heat recovery unit, where both of them have been assumed as constants to simplify the calculation. The equipment efficiencies can be different for each entity $i$; however, in this work, efficiencies of the same equipment in all entities have been assumed as the same. $n_{i,t}^{PGU}$ is the amount of fuel (natural gas in this work) used by the PGU at a specific time $t$, which is a decision variable. Similar to the PGU, the boiler also generates heat by burning natural gas. The amount of natural gas used ($n_{i,t}^{bo}$) is also a decision variable.

The absorption chiller and electric chiller generate cooling by using heat and electricity, respectively. Their outputs ($C_{i,t}^{ac}$ and $C_{i,t}^{ec}$) are calculated based on the coefficient of

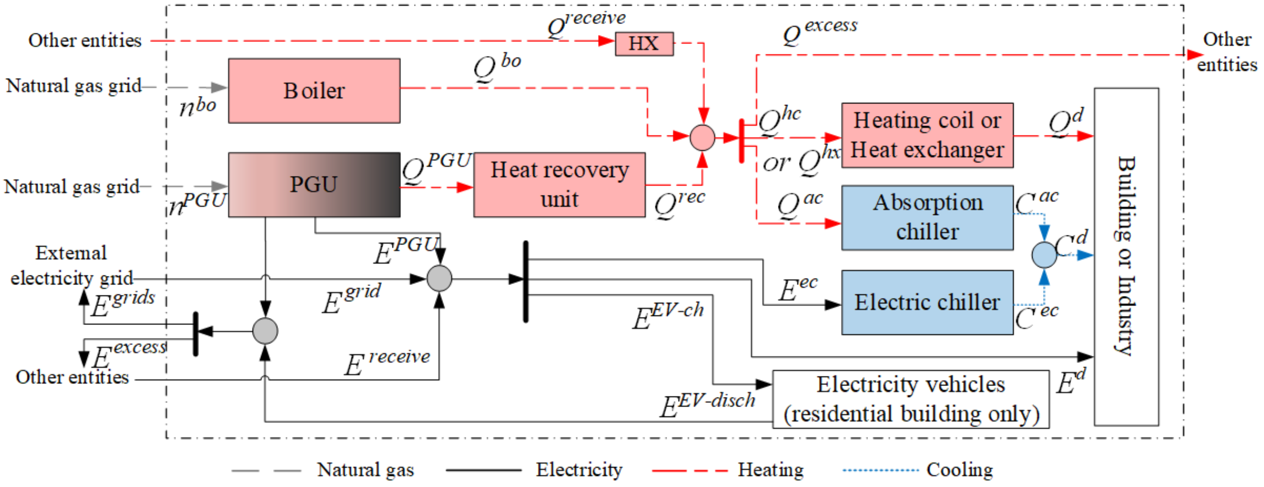

**Figure 1.** A representation of the energy system in one entity.

performance (COP) of the equipment and the decision variables – the amount of heat ($Q^{ac}_{i,t}$) and electricity ($E^{ec}_{i,t}$) used.

$$C^{ac}_{i,t} = COP^{ac}_{i} Q^{ac}_{i,t} \tag{4}$$

$$C^{ec}_{i,t} = COP^{ec}_{i} E^{ec}_{i,t} \tag{5}$$

Besides the decision variables mentioned above, the amount of electricity used to charge the EVs ($E^{EV-ch}_{i,t}$), discharge by the EVs ($E^{EV-disch}_{i,t}$), and the amount of electricity purchased from the grid ($E^{grid}_{i,t}$) are also decision variables.

Each entity in the integrated system can receive and dispatch heat and electricity to the other entities. The amount of heat ($Q^{receive}_{i,i',t}$) and electricity ($E^{receive}_{i,i',t}$) that receive by an entity *i* from entity *i'*, as well as the amount of heat ($Q^{excess}_{i,i',t}$) and electricity ($E^{excess}_{i,i',t}$) that dispatched from entity *i* to entity *i'* are decision variables. In this work, it has been assumed that energy transfer, either heat or electricity transfer, between two entities at a time is in a single direction.

The decision variables mentioned above are operation decision variables that can be manipulated during the operation. The capacity of each piece of equipment ($Cap^{eqp}_{i}$) is the design decision variable that independent of time and cannot be modified once the system has been built. Taking the PGU as an example, the capacity and electricity output follows the relationship below:

$$E^{PGU}_{i,t} \leq Cap^{PGU}_{i} \tag{6}$$

## Energy balances

### Energy demands of industrial plants

Unlike the residential and commercial buildings whose energy demands are stable and are assumed as fixed profiles in this work, the energy demands of the industrial plants are adjustable by changing their production rates. The production rates of plants, $x$, are operation decision variables.

As for plants that have continuous or semi-continuous production processes, the production rate ($x_{i,t}$) represents the amount of product being generated at time $t$, which is one hour in this work. The heating, cooling, and electricity used by each process $p$ of a plant at time $t$ is calculated based on the production rate and the amount of energy required to make a unit of product ($EU^{d}_{i,p,t}$). An example of calculating the electricity demand is shown below:

$$E^{d}_{i,p,t} = x_{i,t} EU^{d}_{i,p,t} \tag{7}$$

As for plants that have batch production processes, the production rate – $x_i$ represents the amount of product being generated in a batch. Then the energy demand at time $t$ can be calculated by dividing the total energy consumption in a whole batch by the time to accomplish the process in a batch. Eq. (8) shows an example of the electricity demand. The binary decision variable $o_{i,p,t}$ is implemented to ensure each process is fully accomplished in a batch.

$$E^{d}_{i,p,t} = x_i EU^{d}_{i,p} o_{i,p,t} / TL_{i,p} \tag{8}$$

$$\textstyle\sum_t o_{i,p,t} = TL_{i,p} \tag{9}$$

### Energy balances of entities

Energy balance equations are developed to ensure the energy demands of an entity can be fully satisfied. Eq. (10) shows an example of the heat balance for a residential building, where $Q^{excess}_{i,i',t}$ is the amount of heat dispatched by the residential building (entity $i$) to entity $i'$. $Q^{receive}_{i,i',t}$ represents the heat received by the residential building from other entities.

$$\frac{Q^{d}_{i,t}}{\eta^{hc}_{i}} + Q^{ac}_{i,t} + \textstyle\sum_{i'} Q^{excess}_{i,i',t} = Q^{PGU}_{i,t} + Q^{bo}_{i,t} + \sum_{i} Q^{receive}_{i,i',t} \tag{10}$$

With multiple production steps, industries can require heating at different temperature levels. Therefore, instead of a single equation for the overall heat balance, like the residential building, heat balance equations for each industrial production process at a different temperature are developed for industries. It ensures the heat transfer is feasible, which is from high temperature to low temperature. $Q^{receive}_{i,i',p,t}$ represents the amount of heat received by each process from other entities.

$$\frac{Q^{d}_{i,p,t}}{\eta^{hc}_{i,p}} + Q^{ac}_{i,p,t} = Q^{PGU}_{i,p,t} + Q^{bo}_{i,p,t} + \textstyle\sum_{i} Q^{receive}_{i,i',p,t} \tag{11}$$

Besides the individual heat balance equation for each process, an overall heat balance equation similar to Eq. (10) is also developed for the entire plant to include the amount of heat used by the absorption chiller and heat dispatched to the other entities. Since the electricity and cooling demands are not differentiated based on temperature levels, electricity and cooling balances are developed for the overall entity.

## Objective function

This work intends to find the optimal design and operation that maximize GHG emissions reduction benefits of the integrated system, measured as the GHGD%. The objective function is set as minimizing the GHG emission ratio (GHGR%) between the two systems to reduce the computation time, as shown in Eq. (12), which is equivalent to maximizing the GHGD%.

$$minGHGR\% = \min \frac{\min GHG_{int}}{\min GHG_{non-int}} \tag{12}$$

As shown in Eq. (12), minimum GHG emissions for both the integrated system and non-integrated system are necessary for calculating the GHGR%. It requires developing and solving optimization problems for both the integrated system and non-integrated system at the same time, which leads to a complex problem formulation. Alternatively, the minimum GHG emissions of the non-integrated system can be expressed as a linear equation based on the sizes of entities. The linear relationship exists because there are optimal operation patterns of equipment for the non-integrated system that does not have energy transfer among entities. When the sizes of the entities change, the optimal operation patterns remain the same, while the capacities of the equipment change correspondingly. The linear equation has been found by solving optimization problems for the non-integrated system under different entity sizes, then performing linear regressions.

# CASE STUDY DESCRIPTION

In this work, energy systems of a residential building with electric vehicles, a supermarket, a confectionery plant, a brewery, and a bakery plant have been used for case studies, as shown in Figure 2.

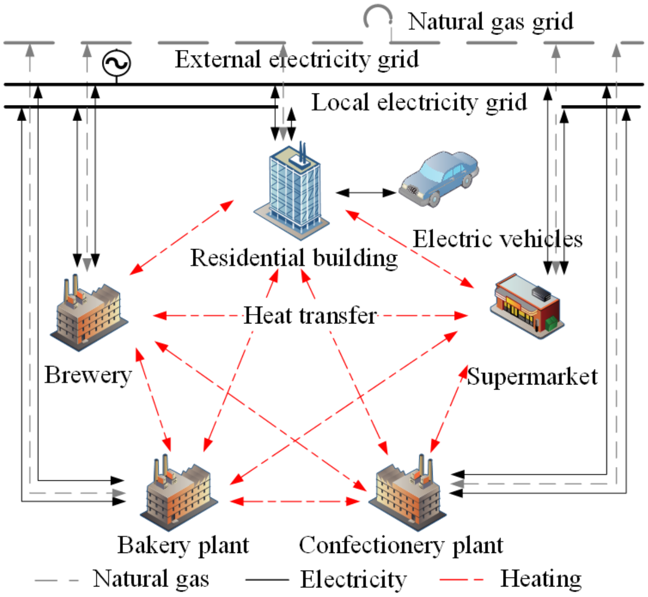

**Figure 2.** A representation of the integrated system.

Among the entities, the residential building and supermarket require more electricity than heating. Their energy demands are imported as fixed profiles, adapted based on information published by Sullivan [5] and Ghorab [6].

The confectionery plant and the brewery have higher heating demands than electricity demands, where the ratio between the heating and electricity demands of the two plants are 3.2 and 3.9, respectively. Both industries have been assumed to have continuous production processes. The bakery plant has a batch production process, which can implement electric baking ovens or gas-powered baking ovens. In this work, the gas-powered baking oven has been assumed as an indirect-fired oven, which uses heat generated by the PGU. When the baking oven is powered by electricity, the bakery plant requires more electricity than heating, where the ratio between the heating and electricity usage is 0.26. The ratio changes to 6.12 when the gas-powered baking oven is used.

In this work, case studies have been performed in both situations where the bakery plant uses electric baking ovens and the situation where gas-powered baking ovens are used. It intends to investigate the impacts of integrating entities with different energy demand patterns on GHG emissions reduction benefits of the integrated system.

## RESULTS AND DISCUSSION

### Integrated energy system with electric baking ovens in the bakery plant

Upon solving the optimization problem, it has been found that when the bakery plant uses electric baking ovens, the integrated system can achieve a maximum GHGD% of 17.5%. It requires the system to integrate 1.07 units of the residential building, 1.07 units of the supermarket, 934 electric vehicles (EVs), a brewery with a capacity of 3,934 kg/hr, and a bakery plant of 5,000 kg/day. There is no confectionery plant in the system. The 1.07 units of the residential building and supermarket stand for a residential building and a supermarket whose energy demands are 1.07 times of the ones mentioned in the Case Study Description section. The ratio between sizes of the entities is the optimal relative entity sizes that maximize GHG emission reduction of the integrated system. As shown in Figure 3, when deviating from this optimal relative entity size, the GHGD% of the integrated system becomes less than 17.5%.

Compared to the non-integrated system, the integrated system purchases 68.0% less electricity from the external grid and uses 82.5% less natural gas for operating the boiler. The reductions lead to the integrated system having lower GHG emissions compared to the non-integrated system. Additionally, the operation of the PGUs in the integrated system increased by 57.9% compared to the non-integrated system. The result indicates allowing energy transfer among entities can increase the operation of the PGUs, which reduces GHG emissions of the entire system.

In the integrated system, the brewery performs as the major electricity supplier, where 95.7% of the electricity transferred among entities is dispatched by the brewery. The electricity is sent to the residential building, bakery plant, and supermarket because the brewery requires more heating than electricity, while the three entities require more electricity than heating. Instead of operating the PGU following the lower electricity demand and using the boiler, the brewery increases the operation of the PGU to generate more heat locally. The associated excess electricity is sent to the residential building, bakery plant, and supermarket.

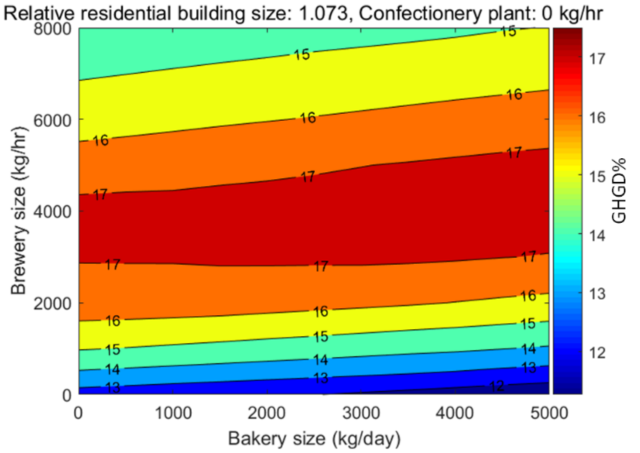

**Figure 3.** GHGD% of the integrated system where the bakery plant uses electric baking ovens.

### Integrated energy system with gas-powered baking ovens in the bakery plant

When the bakery plant uses baking ovens powered by natural gas, a maximum GHGD% of 17.6% can be achieved by the integrated system. The optimal size of the bakery plant is still 5,000 kg/day. The sizes of the residential building and supermarket slightly decrease to one unit, while the optimal capacity of the brewery is 2,812 kg/hr. Similarly, as shown in Figure 4, when deviating from the optimal relative entity size, GHGD% achieved by the integrated is less than the maximum value.

Under this system configuration, the integrated system purchases 60.8% less electricity from the grid and uses 76.1% less natural gas for operating the boilers than the non-integrated system. The operation of the PGU increases by 52.3%.

Since the bakery plant has higher heating demand than electricity demand, instead of an electricity receiver, the bakery plant becomes an electricity supplier. The amount of electricity dispatched by the bakery plant accounts for 16.8% of the total electricity transferred among entities. The brewery still performs as the major electricity supplier of the integrated system, which provides 80.6% of the total electricity transferred among entities. The electricity from both the bakery plant and brewery is transferred to the residential building and supermarket that have higher electricity demands.

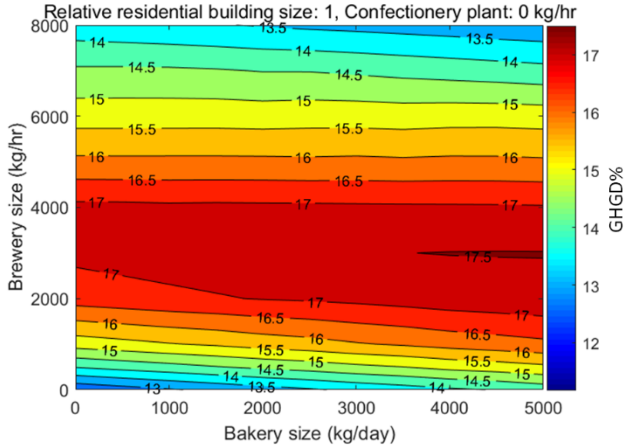

**Figure 4.** GHGD% of the integrated system where the bakery plant uses gas-powered baking ovens.

## Impacts of integrating energy systems with different energy demand patterns

Table 1 shows the highest GHGD% of the integrated system achieved under different relative sizes of the residential building. According to the results, when the relative size of the residential building increases, the highest GHGD% of the integrated system decreases. It is because there are upper bounds on the sizes of industrial plants, which limits increases of the plant sizes. Thus, the integrated system deviates from its optimal relative entity sizes and optimal operation patterns, which leads to the maximum GHGD% cannot be held.

Results in Table 1 also indicate integrating entities with different energy demand patterns leads to slightly higher GHG emissions reduction benefits of the integrated system. Under each of the relative sizes of the residential building, compared to implementing electric baking ovens, using gas-powered baking ovens in the bakery plant leads to the system having a GHGD% of 1% - 2% higher. As shown in Table 1, when the bakery plant has electric ovens that require more electricity than heating, the size of the bakery plant decreases when the size of the residential building increases. When baking ovens are powered by burning natural gas, where the bakery plant has higher heating than electricity demand, the size of the bakery plant remains at its maximum value regardless of changes in the residential building size. Under both scenarios, the sizes of the confectionery plant and brewery, which requires more heating than electricity, both increase. It is because the integrated system tends to keep a balance between the heating demand and electricity demand of the entire integrated system to avoid purchasing electricity from the grid and operating the boilers. Since the residential building requires more electricity than heating, with increases in its size, the electricity demand of the entire system also becomes greater than the heating demand. Thus, when using electric baking ovens, the size of the bakery plant decreases to avoid increasing the electricity demand of the entire system. When implementing gas-powered baking ovens, the size of the bakery plant is already at its maximum level under the optimal relative entity sizes. Therefore, when the size of the residential building increases and the entire system needs to increase its heating demand, the size of the bakery plants remains unchanged.

Overall, the results show that by optimizing the size of entities, a 15.7% - 17.6% of GHG emissions reduction can be achieved by the integrated operation. Such the GHGD% is relatively stable even when there are changes in energy demand patterns of some entities or requirements on the sizes of some specific entities that lead to the optimal entity sizes cannot be followed.

## CONCLUSION

This work quantifies the GHG emission reduction benefits that can be achieved by integrating energy systems of different sectors – residential, commercial, industrial, and transportation sectors. Even if the GHG emission of each operating energy system has been minimized by using the combined cooling, heating, and power (CCHP) system, the GHG emissions can be further reduced by transferring heat and

**Table 1:** Highest GHGD% under different relative sizes of the residential building.

| Relative size of residential building | Electric oven | | Gas-powered oven | |
|---|---|---|---|---|
| | Entity sizes | GHGD% | Entity sizes | GHGD% |
| 1 | Confectionery: 0<br>Bakery: 5,000 kg/day<br>Brewery: 4,000 kg/hr | 17.5% | Confectionery: 0<br>Bakery: 5,000 kg/day<br>Brewery: 2,812 kg/hr | 17.6% |
| 3 | Confectionery: 0<br>Bakery: 4,500 kg/day<br>Brewery: 8,000 kg/hr | 17.1% | Confectionery: 0<br>Bakery: 5,000 kg/day<br>Brewery: 8,000 kg/hr | 17.2% |
| 5 | Confectionery: 1,500 kg/hr<br>Bakery: 4,000 kg/day<br>Brewery: 8,000 kg/hr | 16.6% | Confectionery: 1,000 kg/hr<br>Bakery: 5,000 kg/day<br>Brewery: 8,000 kg/hr | 16.7% |
| 10 | Confectionery: 3,000 kg/hr<br>Bakery: 1,500 kg/day<br>Brewery: 8,000 kg/hr | 15.7% | Confectionery: 3,000 kg/hr<br>Bakery: 5,000 kg/day<br>Brewery: 8,000 kg/hr | 15.9% |

electricity among individual entities. The optimal design and operation of energy systems are determined, including the capacity and operation of equipment, the optimal production rate of plants, and the optimal relative size of entities, considering temperatures of heating demands.

Results from case studies on an integrated system with a residential building, a supermarket, a confectionery plant, a bakery plant, a brewery, and electric vehicles show the integrated operation can lead to a maximum GHG emissions reduction percentage (GHGD%) of 17.6% when the bakery plant uses gas-power baking ovens. When using electric baking ovens, the maximum achievable GHGD% is slightly lower – 17.5%.

The highest GHGD % can be maintained between 15.7% and 17.6% by optimizing the sizes of entities. Thus, even when there are requirements on sizes of specific entities and the optimal relative entity sizes cannot be followed, or there are mitigations on industrial production processes that change energy demand patterns of the entities, the integrated system still shows benefits in reducing GHG emissions than the non-integrated system.

## ACKNOWLEDGEMENTS

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