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Greenhouse electrification via transactive energy management strategy

Reza Babaei, David S-K Ting, Rupp Carriveau*
Turbulence and Energy Laboratory, University of Windsor
401 Sunset Ave, Windsor, ON, Canada
**Correspondence author: rupp@uwindsor.ca*

Abstract
Distributed energy resources have grown significantly in Canada and the world over the past decade, particularly in the agricultural sector. As P2P (peer-to-peer) energy trading plays a fundamental role in renewable energy uptake and system flexibility for the low-carbon energy transition, this paper provides an overview of this approach from a techno-economic standpoint for two greenhouses located in Leamington, Ontario. The real-time site solar irradiation, ambient temperature, and load demand over 8760 h have been utilized to drive the designs. In this investigation, two cases are assessed for pepper greenhouse: Case I: energy purchase from the grid and Case II: energy purchase from excess energy of neighbor which is cucumber-tomato greenhouse. The integration of 50 kW PV/1 kWh battery/35 kW converter achieves the feasibility criteria by recording net present cost (NPC) and cost of energy (COE), which are $29.6k and $0.044/kWh, respectively.

Nomenclature

AC	alternating current	inv	inverter
ann,tot	total annualized cost	n	lifetime (year)
COE	cost of energy	NOCT	nominal operating cell temperature
Cpc	maximum power coefficient	NPC	net present cost
CRF	capital recovery factor (%)	pc	power coefficient
DC	direct current	peak	peak load demand
f	derating factor (%)	PV	solar photovoltaic
F_0	generator fuel curve intercept co-efficient (L/h/ rated kW)	RF	renewable fraction
G	incident radiation at standard test conditions (1 kW/m^2)	SOC	state of charge
HES	Hybrid energy system	Y	rated capacity (kW)

1. Introduction

A growing consumer preference for renewable resources and battery storage to reduce greenhouse gas emissions is causing significant changes in the global energy sector [1]. Among the potential renewable energy systems across Canada, grid-connected PV systems are at or above grid parity, and the return on investment (ROI) for PV applications varies by province and utility [2].

Canada's PV power generation has achieved a solar capacity of 2,399 MW by 2023 compared to 2,111 MW in 2020 [3]. It is a sustainable energy source that has proven itself as a net energy producer for the last 20 years. The energy conversion efficiency of PV is improving to the point where the energy payback period is less than other alternatives [4]. These benefits also come with the following challenges including vast land requirements or incompatibility for powering densely populated cities or being intermittent and challenging to predict especially for agricultural sectors.

However, when prosumers have surplus power, they can reconcile it, store it in energy storage, feed it back to the grid, or sell it to other energy consumers. The direct trading of energy between consumers and prosumers is called peer-to-peer (P2P) energy trading and is deployed on the concept of the "P2P economy" (also known as the sharing economy) [5]. Energy trading refers to the buying and selling of energy products with the intention of turning a profit, such as oil, natural gas, and electricity. Energy trading is an essential component of the global energy

*Professor, corresponding author, rupp@uwindsor.ca
†Full Professor

industry, and it is essential to ensuring that there is a steady supply of energy that is both affordable and dependable for everyone [6].

In recent years, P2P energy trading methods have been explored at the distribution network level. Ref. [7] conducted a study proposing two strategies for determining the trading preferences of households participating in P2P energy trading. One strategy focused on balancing excess generation and consumption between prosumers and consumers, and his other was based on proximity between peers. Simulation results for data collected in residential areas in the Netherlands indicated that P2P energy trading reduces interaction with the traditional utility grid and increases energy trading, especially when trading is based on proximity. In Ref. [8] a paradigm of P2P energy exchange between neighboring microgrids is proposed to improve local distributed energy resources (DER) utilization and save energy charges for all microgrids. Ref. [9] integrates a demand-side management system tailored to her P2P energy transactions between households into smart grids to minimize energy costs. Ref. [10] proposed an energy-sharing model with price-based load control. In [11], a non-cooperative game-theoretic model of competition among demand-response aggregators to sell energy stored in energy storage devices was presented.

Reviewed studies show that the integration of the infrastructure models can be cost-effective for residential and commercial purposes. This investigation demonstrates an overview of the energy trading approach from a techno-economic standpoint for two greenhouses located in Leamington, Ontario by comparing energy purchases from the central grid versus one neighboring greenhouse. Basically, neighboring greenhouses engaging in electricity peer-to-peer pricing strategy arrangements can be advantageous for several reasons:

1. **Renewable Energy Incentives:** The neighboring greenhouse will have access to renewable energy incentives or government subsidies that allow them to offer electricity at a discounted rate, encouraging the adoption of clean energy sources in the area.
2. **Local Energy Resilience:** By selling electricity at a competitive price, the neighbor may be contributing to local energy resilience, reducing reliance on the centralized grid during peak demand periods to avoid getting affected by power outages in the harsh weather condition (common in Canada and southern Ontario) that affect crop production.
3. **Sustainable Practices:** The neighbor will have a strong commitment to sustainable practices and aims to support the local community by providing affordable renewable energy options.
4. **Community Collaboration:** Sharing electricity in the neighboring greenhouses fosters a sense of community collaboration by offering electricity at a lower rate to their neighbors, promoting a stronger sense of local energy sharing.
5. **Local Economic Development:** The neighbor's decision to offer electricity at a lower rate might align with local economic development goals, attracting businesses and residents to the area.

1.1 Case Study Description

Greenhouses are widely used in agriculture to grow crops throughout the year, regardless of seasonal variations. In Southern Ontario, particularly in the town of Leamington, greenhouses play a significant role in the local economy and food production. Leamington, located in Essex County, Ontario, is often referred to as the "Tomato Capital of Canada" due to its extensive greenhouse industry. The region benefits from favorable climatic conditions, with warm summers and relatively mild winters, which make it suitable for year-round greenhouse cultivation. Electricity is a significant energy source in greenhouses, primarily used for supplemental lighting, ventilation systems, irrigation, and other equipment. Grow lights are employed to supplement natural sunlight, especially during the shorter daylight hours in winter. Efficient ventilation systems help control temperature and humidity levels, ensuring optimal growing conditions for the plants. The studied locations are two greenhouses located in Leamington, Ontario, Canada a region with a cold climate and high potential for harvesting agricultural crops. As depicted in Table 1 and Table 2, the size and main crop type of pepper greenhouse are 80,937 m^2 and peppers, respectively. Also, the size and main crop type of cucumber-tomato greenhouse are 78,913 m^2 and peppers/tomatoes, respectively.

Table 1. Overall description of pepper Greenhouse

Parameter	Description
Crop Type	Peppers

Size	20 acres (80937 m^2)
Greenhouse Material	Double Poly
Lighting	Unlit

Table 2. Overall description of cucumber-tomato greenhouse

Parameter	Description
Crop Type	Cucumbers Tomatoes
Size	19.5 acres (78913.7 m^2)
Greenhouse Material	16 acres double poly with IR roof and walls 3.5 acres glass roof with double poly walls
Lighting	HPS and LED 6 acres unlit

1.2 Meteorological Data

Figure 1 illustrates solar irradiation and ambient temperature in Leamington, Ontario (42.05° N, 82.60° W). The average data for ambient temperature, and solar irradiation, was collected from NASA's meteorological resource data center (NASA) [12]. The area’s average solar irradiation, clearness index, and ambient temperature are 3.82 kWh/m^2/day, 0.483, and 10.1 °C, respectively.

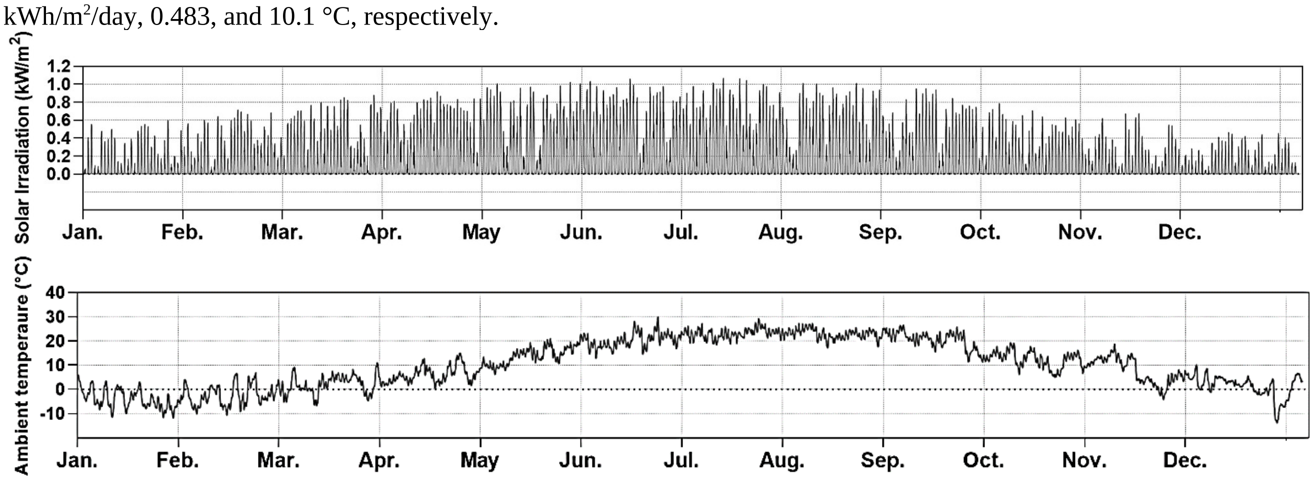


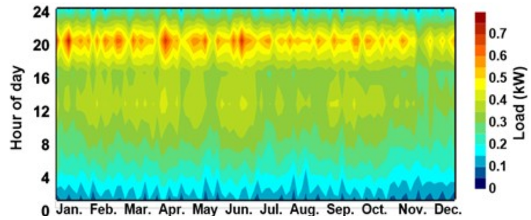
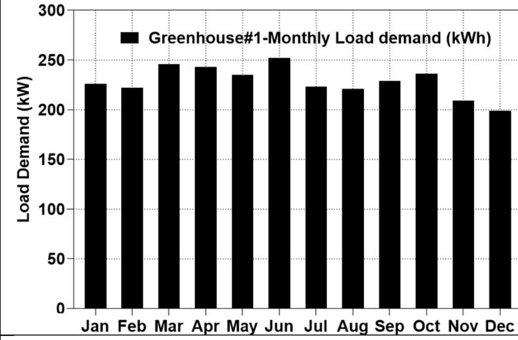
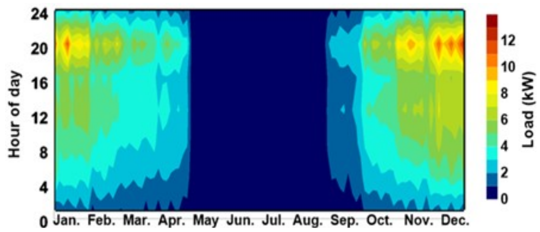
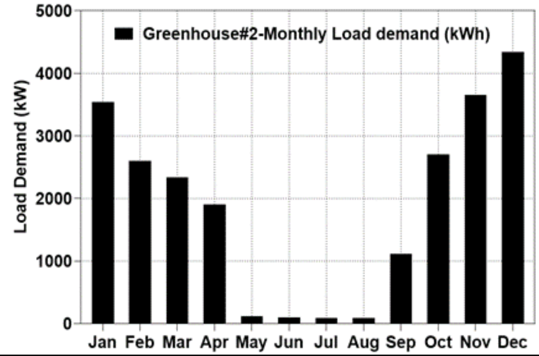
Figure 1. Schematic diagram of energy trading generation configuration

1.3 Electrical data

The load demand for greenhouses is presented in Table 3. The daily average load of pepper Greenhouse and cucumber-tomato greenhouse is estimated to be 7.5 kWh/day and 61.9 kWh/day with day-to-day variability and time-step variability of 10% and 20%, respectively. Further, in pepper greenhouse, the peak load occurs during the summer reaching up to 250 kW in June, and during the fall and winter, electricity consumption reaches its lowest values. Conversely. Electricity drops in spring and summer cucumber-tomato greenhouse and reaches its highest value in December by 4,200 kWh.

Table 3. Monthly and annual electric load profile in Leamington

Greenhouse	Hourly profile	Monthly profile

Pepper green-house	 Load factor: 0.23, Average load: 7.5 kWh/day	
Cucumber-tomato green-house	 Load factor: 0.11, Average load: 61.9 kWh/day	

1.4 Economic formula

I. Net Present Cost (NPC): The components' optimal design is achieved according to the NPC, which is the sum of all expenditures and profits occurring over the project's lifetime. To calculate the overall NPC of a project, the following equation is utilized [14]:

$$C_{npc,tot} = \frac{C_{ann,tot}}{CRF(i,n)} \tag{1}$$

where $C_{ann,\,tot}$ is the yearly cost ($/year), i is the annual interest rate (%), T_P is the lifetime of the project (year), and $CRF(i,n)$ is the capital recovery factor, determined by the equation below [15], [16]:

$$CRF(i,n) = \frac{i(1+i)^n}{(1+i)^n - 1} \tag{2}$$

Also, the following equation is used to estimate the yearly interest rate (%) [17].

$$i = \frac{i-f}{1+f} \tag{3}$$

where i is the annual inflation rate (%).

II. Cost of energy (COE): One of the most important indicators for assessing the cost-effectiveness of HES. The COE is the average cost of a HES divided by the total served electrical energy (kWh), which can be determined by Eq. 4 [18].

$$COE = \frac{C_{ann,tot}}{L_{ann,load}} \tag{4}$$

Here, $L_{ann,load}$ is the overall electricity consumption during a year (kWh/year), and $C_{ann,tot}$ is the total yearly cost ($/year).

The battery stores electricity in a chemical form, and subsequently, this stored energy can be recharged and reused to supply continuous operation as required. The minimum state of the battery is set at 20%, and it is crucial to avoid allowing the battery charge to drop below this threshold to ensure the long-term durability of the battery bank. The following equation shows how values of battery energy can be estimated [19].

$$Q_{battery} = Q_{battery,0} + \int_0^{\tau} V_{battery} I_{battery} dt \tag{5}$$

$Q_{battery,0}$(kWh) is the initial battery charge, $V_{battery}$(V) is the battery voltage and $I_{battery}$(A) is the battery current.

The state of battery charge is expressed by Eq. (6).

$$B_{soc} = \frac{Q_{battery}}{Q_{battery,max}} \times 100(\%) \tag{6}$$

The converter maintains the flow of energy between DC and AC, here equivalent to either an inverter or rectifier. The converter converts DC power from the PV module and battery output into AC. The excess solar energy generation is also stored in the battery storage system [20]. The power rating of the converters can be obtained from the following equation [21]:

$$P_{inv} = \frac{P_{peak}}{\eta_{inv}} \tag{7}$$

In conducting the current study, several key assumptions were made to facilitate the financial and road map. These assumptions include deeming the availability of adequate renewable energy resources such as solar or wind, assuming a certain level of technology efficiency and reliability, having roughly similar energy demand and consumption patterns based on historical data, Interest rate of 4%, project lifetime of 10 years, grid purchase and sales rate of $0.1/kWh and $0.05/kWh. These assumptions provide a foundation for the study, enabling a comprehensive assessment of the potential benefits, challenges, and overall feasibility of adopting renewable energy as a sustainable and reliable energy solution.

1.5 Optimization Strategy

In the intended optimization strategy, whenever the energy supplied by renewable resources and the stored energy is not adequate to meet demand, the central grid is used to satisfy the electrical load at its maximum energy. Any surplus energy extracted from renewables charges the storage units or is sold to the central grid. Figure 2 displays the deemed mathematical controlling strategy for this study.

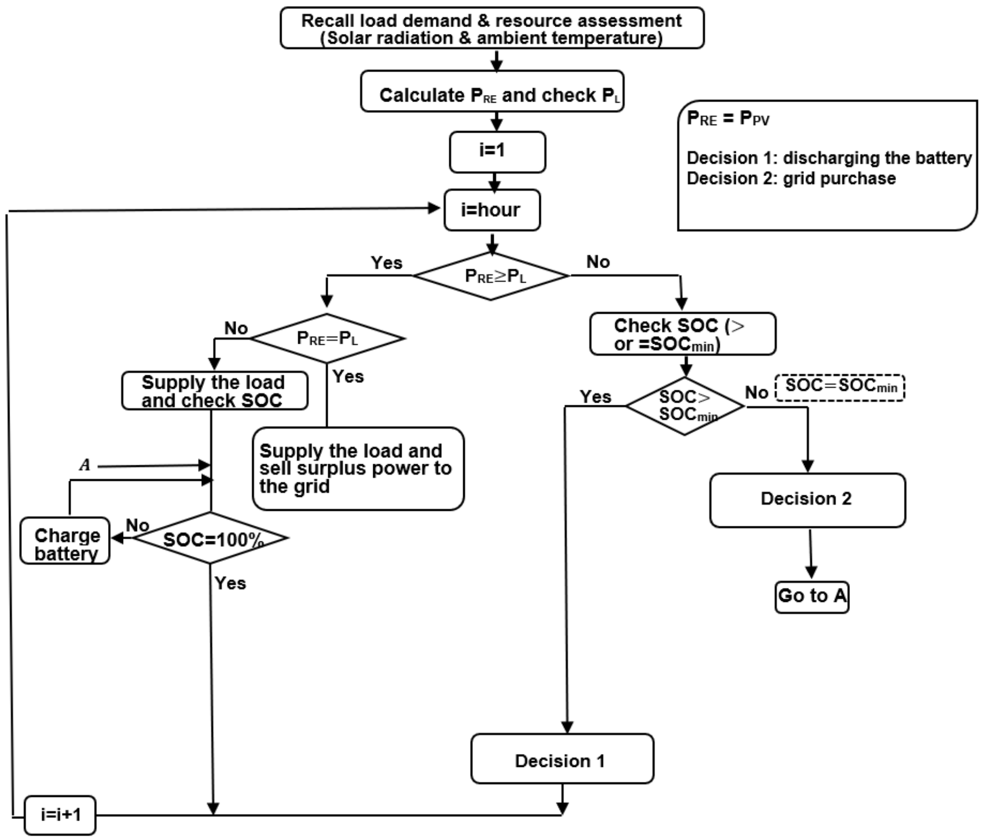


Figure 2. Optimization algorithm of grid-connected PV/battery hybrid energy system

1.6 System configuration

In this investigation, we assumed two scenarios: Scenario I: energy purchase from the grid and Scenario II: energy purchase from the neighbor. Pepper greenhouse is the building where these two scenarios will be applied on. the cucumber-tomato greenhouse has a significantly higher load demand to satisfy compared to pepper greenhouse. Then, the excess energy coming from solar panels located at cucumber-tomato greenhouse's site transfers to pepper greenhouse. Figure 3 illustrates the schematic of the intended system configuration connected to the grid for power purchase and neighbor for power-sharing. Tables 4 and 5 depict the summary of the PV system and battery specifications.

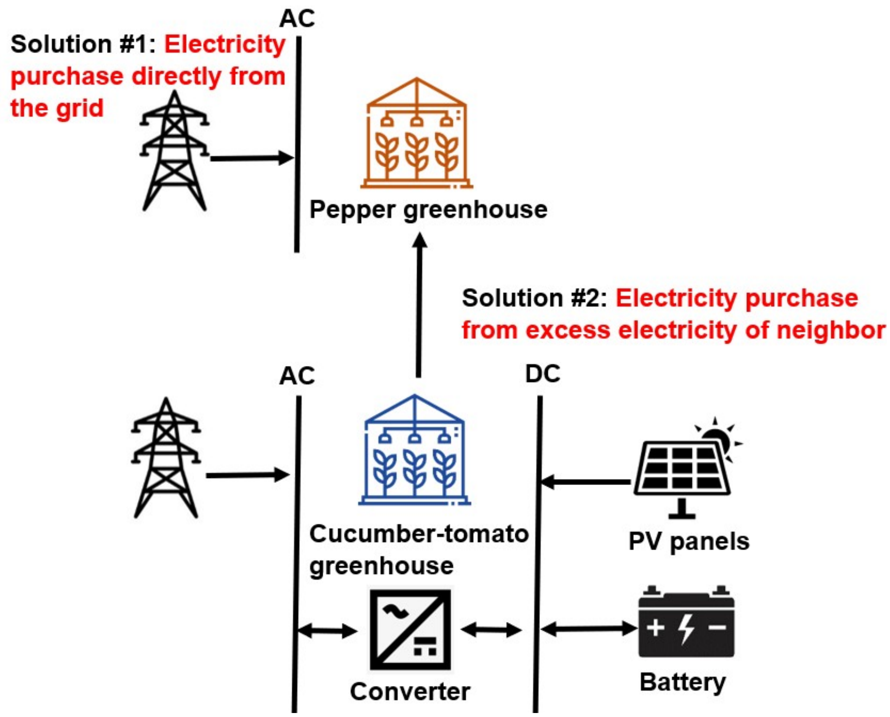


Figure 3. Schematic diagram of energy trading generation configuration

Table 4. Photovoltaic system: electrical specifications [22]

Parameter	Value
Individual Panel's Nominal Output (P_{max})	330 W
Power Tolerance	0/+5 W
Voltage at P_{max} (V_{mp})	34.35 V
Current at P_{max} (I_{mp})	9.61 A
Maximum System Voltage	1500 V
Maximum Series Fuse Rating	20 A
Module Efficiency	19.78%
Solar Cells Size	158.75x158.75 mm / 6.25x6.25"
Dimensions	1665x1002x40 mm / 65.55x39.45x1.57"
Weight	18.6 kg / 41.01 lbs
NOCT (Nominal Operation Cell Temperature)	45±2 °C
Operating Temperature	-40 °C ~ +85°C

Table 5. Overall characteristics of battery configuration [18]

Parameter	Value
Nominal voltage (V)	**6**
Nominal capacity (kWh)	1
Nominal capacity (Ah)	167
Efficiency (%)	90

2. Results and Discussion

This section presents an economic analysis of pepper greenhouse's energy procurement strategy, comparing its current purchase of energy from the central grid with the potential alternative of sourcing solar energy from its neighboring greenhouse. The aim is to evaluate the financial implications of these two options and understand how they may impact the greenhouse's financial performance. The analysis takes into account various factors, including operational costs, energy prices, and long-term sustainability. It assumes an annual increase of 4% in electricity purchase rates from the central grid until 2030 to assess the potential effects of changing energy procurement methods.

2.1 Techno-economic Results

Techno-economic results provide valuable insights into the financial feasibility and viability of renewable energy options. They allow decision-makers to evaluate the costs, benefits, and potential returns associated with adopting renewable energy technologies. Such analysis plays a crucial role in informing strategic planning, investment decisions, and policy formulation, ensuring the successful integration of renewable energy into the energy landscape and fostering a sustainable future. The feasible solution for cucumber-tomato greenhouse is represented in Table 6. In our case, a feasible HES can generate sufficient electricity to meet its own load demand and the excess energy can be utilized to satisfy the neighbor’s load demand at the same time. The combination of 50 kW PV/1 kWh battery/35 kW converter achieves the feasibility criteria by recording NPC and COE, which are $29.6k and $0.044/kWh, respectively. The total yearly energy generation is 88.352 kWh out of which 84.5% (74,651 kWh) and 15.5% are produced by PV modules and grid purchases, respectively. A summary table of energy purchases from the grid and from the neighbor for 8 years of the project lifetime is presented in Table 7,8 and Figure 4. It shows that it is more cost-effective if the owner of pepper greenhouse buys the energy from the neighbor(cucumber-tomato greenhouse) which could result in cost savings of ~57% until 2030 [23]. The traded cost of energy and electricity rate is assumed to increase by 4% as per the projected inflation rate.

Table 6. Techno-economic result of the optimal configurations using in cucumber-tomato greenhouse

PV	Battery	CNV	NPC	COE	Renewable fraction	Electricity production	PV production	Grid purchase	Transferred energy to pepper greenhouse
kW	kWh	kW	$k	kWh/$	%	kWh/year	kWh/year	kWh/year	kWh
50	1	35	29.6	0.044	84.5	88,352	74,651	13,701	3,899

Table 7. Summary of grid purchase rates and total grid purchases until 2030 in pepper greenhouse until 2030

Year	Grid purchase rate ($/kWh)	Energy purchase from the grid ($)
2023 (base year)	0.100	274.03
2024	0.104	285.0
2025	0.108	295.0
2026	0.111	305.3
2027	0.115	316.0
2028	0.119	327.1
2029	0.124	338.5
2030	0.128	350.4
Total	-	2,491.1

Table 8. Summary of electricity rates and total purchases from the neighbor (cucumber-tomato greenhouse) until 2030

Year	Traded energy cost between neighbors ($/kWh)	Energy purchase from the neighbor ($)
2023 (base year)	0.0440	171.6
2024	0.0460	179.2
2025	0.0478	186.4
2026	0.0497	193.9
2027	0.0517	201.6
2028	0.0538	209.7
2029	0.0559	218.1
2030	0.0582	226.8
Total	-	1,587.2

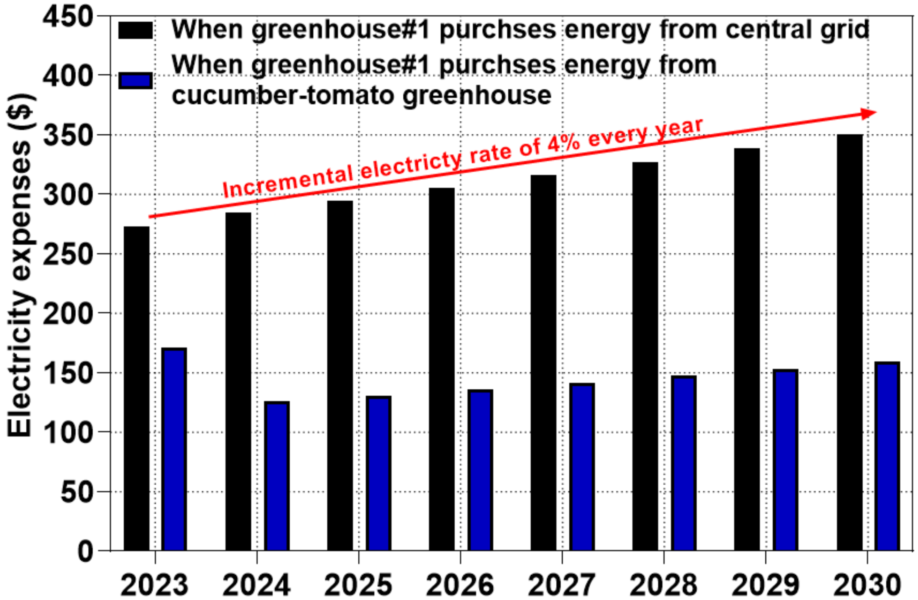


Figure 4. Comparison of energy purchase from the central grid versus from the neighbor

2.2 Financial breakdown of the optimal solution

Table 9 demonstrates the breakdown of net present costs by component and cost type for the cucumber-tomato greenhouse. The sum of all costs, including capital, replacement, operation and maintenance, and fuel costs, minus the salvage cost at the end of the project's lifetime, is known as the net present cost (NPC). The highest contribution of the cost is dominated by the total capital expenditure for the components at $54,250. PV modules and converters have achieved the highest expenses during the project lifetime at $33,697 and $8,100, respectively.

Table 9. Cost breakdown of the optimal solution using in cucumber-tomato greenhouse

Component	Initial cost ($)	Operation & maintenance ($)	Salvage cost ($)	Total cost ($)
Li-Ion battery	500	82	-114	467
Grid	0	-12,627	0	-12,627
PV system	43,250	10,217	-19,769	33,697
Converter	10,500	0	-2,400	8,100
Total	54,250	-2,329	-22,283	29,638

Figure 5 displays the yearly profile of the optimal energy solution of the cucumber-tomato greenhouse. PV modules can produce 84.5% of the yearly energy and 15.5% of energy is purchased from the grid. The energy contribution can be satisfied only by using PV modules from May to August. The highest grid purchase occurs from November to January ranging from 2.5 MWh to 3 MWh. Figure 6 illustrates the excess energy. Figure 5 shows the yearly excess energy profile which is defined as the traded energy produced from the cucumber-tomato greenhouse to satisfy the load requirement of cucumber-tomato greenhouse. The total excess energy from cucumber-tomato greenhouse is 3.8 MWh/year which is more than what pepper greenhouse needs.

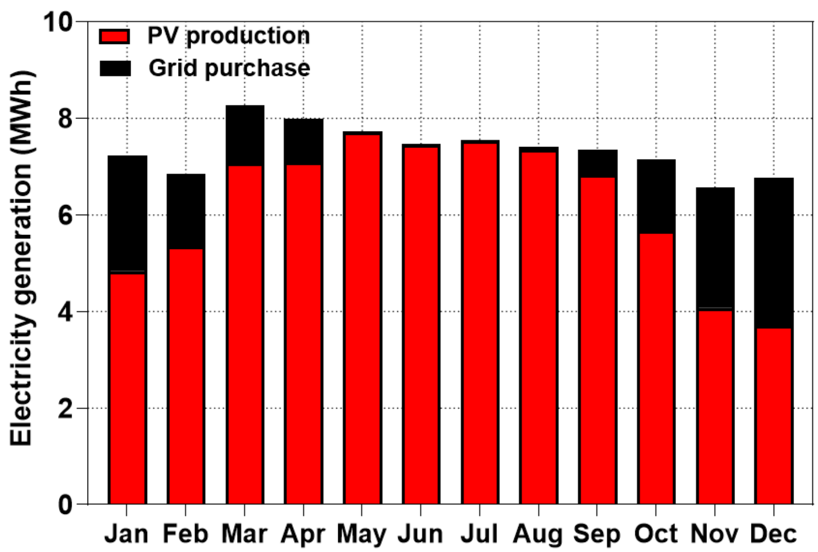


Figure 5. Energy generation profile of the optimal solution for cucumber-tomato greenhouse

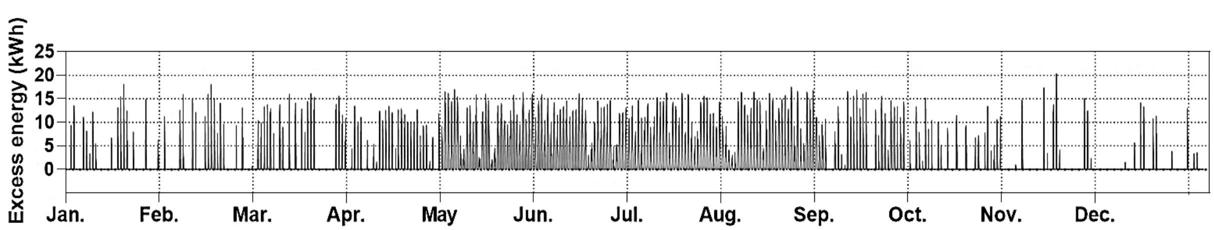


Figure 6. Yearly excess energy produced from cucumber-tomato greenhouse to provide energy for pepper greenhouse

2.3 Validation of data accuracy compared to the relevant research studies

Validating the net present cost (NPC) and the cost of energy (COE) together in research studies is crucial for several reasons. Firstly, the NPC provides a comprehensive evaluation of the total costs and benefits associated with a project over its lifetime. This includes capital expenses, operational costs, maintenance, and revenue generation. By validating the NPC, researchers ensure that the economic evaluation accurately reflects the financial feasibility of the project. Secondly, the COE represents the cost of producing a unit of energy from the project. By validating the COE alongside the NPC, researchers gain a complete understanding of the economic viability of the project. This information is essential for decision-making processes, as stakeholders can assess the costs and benefits of different options and make informed choices based on accurate economic evaluations. Table 10 presents a summary of recent research on renewable energy systems worldwide and their winning financial values.

Table 10. Comparison of the current result with some of the previous analyses

Status	Ref., year	Location	Energy system	COE* ($/kWh)	NPC* (k$)
Off-grid	[24], 2019	Rajshahi, Bangladesh	PV/DG/BT	0.310	421.1
	[18], 2022	Kwazulu Natal, South Africa	PV/DG/BT/HKT	0.258	13.7
	[25], 2017	Kilis, Turkey	PV/DG/BT	0.130	6.1
	[26], 2019	Korkadu, India	BG/PV/WT/BT	0.140	30.1
	[27], 2021	Rangpur, Bangladesh	PV/DG/WT/BT	0.208	152.0
On-grid	[28], 2020	Tehran, Iran	DG/PV/WT/BT	0.132	7.4
	[29], 2016	Bizerte, Tunisia	DG/PV/WT/BT	-	57.5
	[30], 2021	Campinas, Brazil	PV/BT	0.096	182.0
	Current Study	**Leamington, Canada**	**PV/BT**	**0.044**	**29.6**
DG= diesel generator, PV= photovoltaic system, BT= battery, WT= wind turbine, HKT= hydrokinetic turbine					

Conclusion

The principal objectives of this paper were to determine the techno-economic feasibility analysis of energy trading between purchasing energy from the grid versus its neighbor which has renewable energy infrastructure. The designs have been driven by the site's real-time solar irradiation, ambient temperature, and load demand over 8760 hours. The most profitable hybrid energy solution was observed by the integration of PV module, battery, and converter connected to the central grid in Ontario. The integration of 50 kW PV/1 kWh battery/35 kW converter achieves the feasibility criteria by recording NPC and COE, which are $29.6k and $0.044/kWh, respectively. The total yearly energy generation is 88.352 kWh out of which 84.5% (74,651 kWh) and 15.5% are produced by PV modules and grid purchases, respectively. The total capital expenditure was calculated at $54,250, which contributed the majority of the cost. From May to August, the energy contribution can only be met by using PV modules. Furthermore, the highest grid purchases, averaging 2.5 to 3 MWh, occur from November to January.

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