Chapter 1

# Diversifying Electricity Customer Choice: REVing Up the New York Energy Vision for Polycentric Innovation

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Additional information is available at the end of the chapter

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**Abstract**

Electric utility business models are changing to integrate new technologies and distributed energy resources (DER). Diversifying energy mix and customer choices are both novel and useful in understanding key drivers of this transformation, including distribution system planning and customer-service options. Practical implementation of these solutions, however, shows that without proper planning, energy diversification could come at very high social and economic costs. For example, regulators have been slow in implementing policy, regulatory, and business model constructs that promote customer choice to animate high levels of grid reliability and resiliency. Equally important is how viable existing utility business models are to navigating transformation processes, including strategic resource management, revenue model, customer interface, and value propositions. This chapter discusses our use of the Hamel business model to offer strategic analysis of Reforming the Energy Vision (REV), which is aimed at decarbonizing New York's energy sector and increasing customer choice and control. Specifically, we build from existing literature to argue that implementing distribution management systems (DMS) in which customer choice and DERs are prominent requires a shared or 'polycentric,' networked business-model innovations that build on competitive and comparative advantages of existing institutions to meet the growing demand for electricity services and utility strategic goals.

**Keywords:** reforming the energy vision, distributed energy resources, business model, polycentric innovation, utility choice management, Hamel framework

## 1. Introduction

The electric utility landscape is experiencing rapid and unprecedented transformation. A powerful confluence of structural, technological, and socio-economic factors is driving this change. Distributed technologies (e.g., distributed generation, energy storage, flexible demand, and advanced power electronics) are competing in the emerging distributed utilities market and, as a result, putting pressure on investors and regulators to consider utility choice management (UCM) opportunities that promote more capital-efficient options for the provision of electricity services [1]. The second installment of the Quadrennial Energy Review (QER), released in the winter of 2017, recommends spending $300–$500 billion in grid modernization, noting that it "is the platform for the twenty-first century electricity system, bringing significant value associated with lower electricity bills due to fuel and efficiency savings, more electricity choices, and fewer and shorter outages" [2]. The QER also recommends that utilities deploy a "wide range of new, capital-intensive technologies" to modernize their aging infrastructure, and to "support increased reliability, security, value creation, consumer preferences, and system optimization and integration at the distribution level." At the distribution utility level, the electric utility faces a fundamental challenge. Besides investments needed for grid modernization, the emergent role of the consumer as prosumer coupled with new priorities, such as enhancing electricity reliability, affordability, resilience, environmental protection, and grid security, are driving the current evolution in the industry and destabilizing the century-old government-regulated, vertically integrated, monopoly business model that is the energy utility.

The pressure to revamp the electric utility landscape is evident not only in the contiguous United States—for example, New York, California, Illinois, Massachusetts, and North Carolina—but also in Hawaii and Alaska [3]. The dominating trend of fast-flexing renewable energy sources, mostly solar and wind power, continues to underpin early retirement of baseload power-generating sources such as nuclear, coal, and natural gas steam generator [4]. The growth of solar and wind power, flat or declining electricity demand, and cheap natural gas have been cited as the reasons for the decline in electricity prices and economic viability of baseload energy generation sources such as nuclear energy [5, 6] and thus declining revenues for utility generators. As a result, strategic improvement of utility structure and planning to create new choices for customers requires explicit recognition and response to these challenges as well as local and regional idiosyncratic design and operational obstacles. For instance, utilities across the country face distinctive characterizations of the so-called 'death spiral' - the cycle of eroding market share to distributed energy prosumers that raises costs on remaining utility customers, leading to accelerated market losses [7, 8]. Nationwide, the 'death spiral' debate is substantial. According to Accenture, estimated utility sector revenue erosion in the United States resulting from increased distributed generation and gains in energy efficiency could be between $18 and $48 billion by 2025, depending on status quo, demand disruption, or perfect storm assumptions [9] (**Figures 1** and **2**). However, this debate continues with varied levels of concerns across states and regional electricity markets like PJM Interconnection, Midcontinent (MISO), Texas (ERCOT), California (CAISO), New England (ISO-NE), and New York (NYISO). The effect of the dreaded 'death spiral,' if it materializes, will be felt differently across the nation's utilities. Similarly, aging infrastructure concern due to long periods of low investments in grid modernization, changing supply and demand profiles, and investments in research and development (R&D) commitments are not geographically ubiquitous [2, 6, 10].

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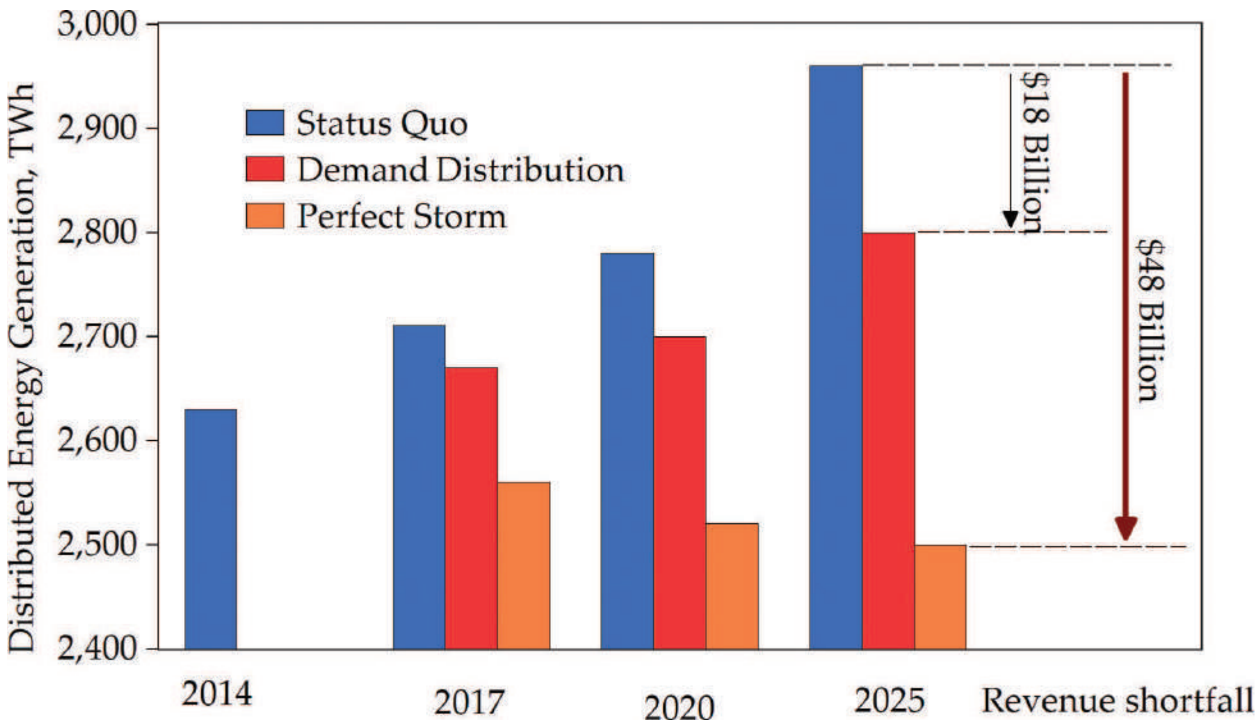


**Figure 1.** Estimated erosion of utility revenue.

Recent studies by McKinsey & Company conclude that energy storage is already economical for many commercial customers [11]. Rapidly falling solar photovoltaics (PV) prices coupled with low-cost storage will create an increasing number of residential and commercial customers who will meet their electric service needs through distributed generation. Falling storage prices have the potential to transform the power landscape by smoothing out the variations in power associated with variable electricity power, such as solar and wind, and achieve 24/7 reliability. Frew et al. review pathways to a highly renewable U.S. electricity future and observe that design of policies such as renewable portfolio standard (RPS) targets, Federal Energy Regulatory Commission (FERC) orders, emission regulations, greater regional coordination and geographic aggregation, and energy storage is critical to the emergent distributed electricity market [12]. While there is disagreement on the structure of electricity market design, regional coordination planning, flexibility mechanisms required to help mitigate the variability and uncertainty challenges arising from a high penetration of intermittent electricity generation, and how soon and how fast a highly renewable electricity future can occur, the trend is similar for many parts of the United States.

Several response strategies have emerged shaped by policy, market, public oversight, and financing support. These include utility-as-platform models like the New York Public Service Commission's (NYPSC) grid and market modernization initiative called Reforming the Energy Vision (REV), utility as a smart integrator, and electric services operator model [13]. The New York's REV vision recognizes that the path for a distributed utility model which promotes a highly renewable electricity future in the state will not be linear. Hence, the vision lays out multiple sets of solutions to various aspects of electricity market design and operations,

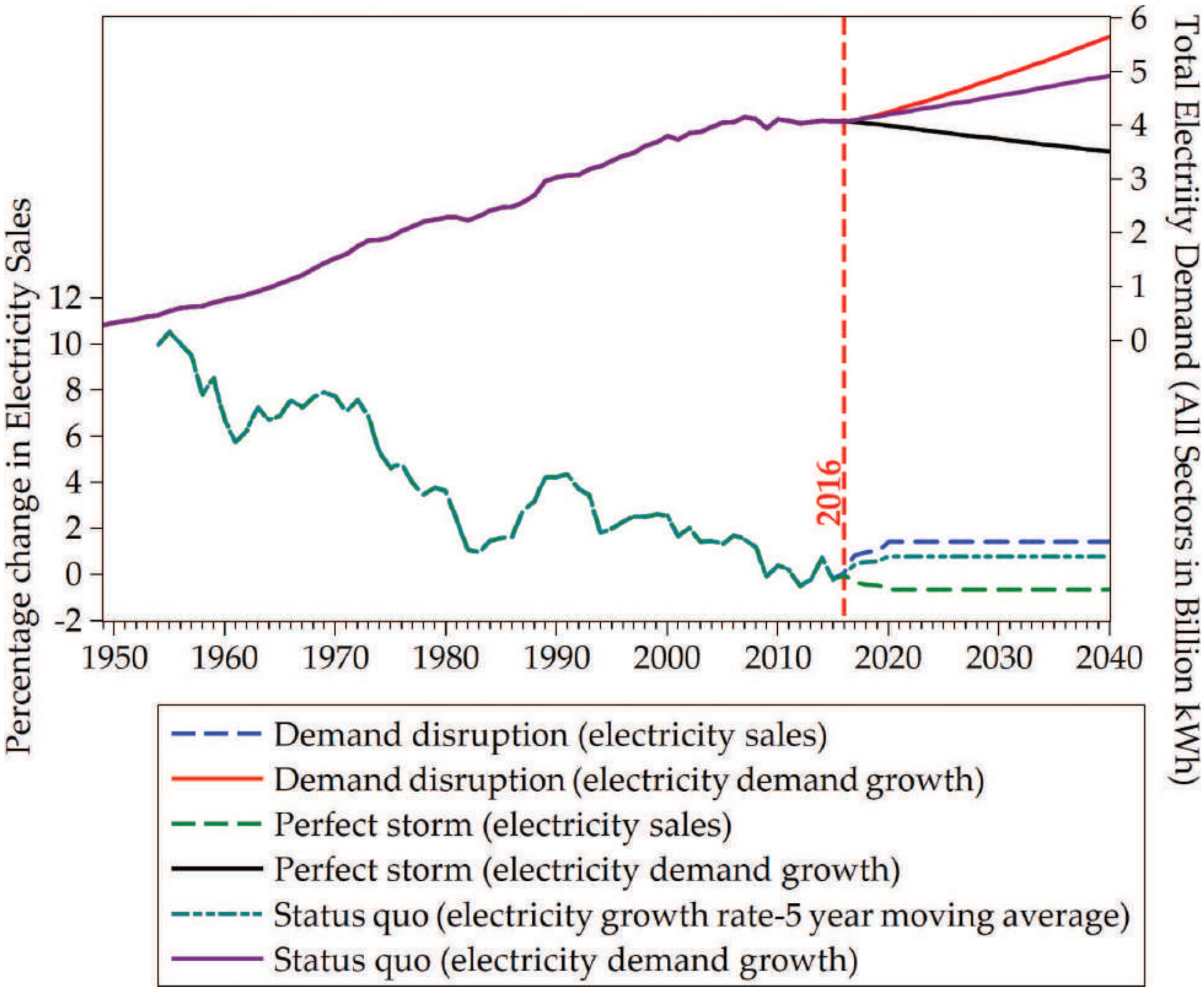


**Figure 2.** How the adoption of energy demand-disrupting technologies could erode energy demand and utilities' revenues through 2040.

taking into consideration utility market composition and regulatory structures. This paper evaluates a typology of policy, regulatory, and business model constructs for diversifying energy mix and utility choices, arguing for a polycentric approach to carry out utility business-model innovation and electric power market design that might allow this suggested future to play out in the real world. Section 2 discusses challenges, limitations, and opportunities of utility-side and customer-side business models. Section 3 evaluates the Hamel framework, and Section 4 applies this framework to the New York's REV. Section 5 concludes the paper.

## 2. Theoretical framework

### 2.1. Business models

The business model concept offers a valuable unit for evaluating new market ventures and business practice [14–16]. There is no universally accepted definition of a business model. However, authors in different industries have proposed a litany of definitions. Ref. [17]

defines a business model as "the rationale of how an organization creates, delivers, and captures value" while [18] describes a business model as "the heuristic logic that connects technical potential with the realization of economic value." Ref. [19] defines a business model as "a representation of the underlining core logic and strategic choices for creating and capturing value within a value network." As an analytic tool, the concept has been widely used in studying investors' preference for service-driven business models [15], energy service company (ESCO) [16], micro-generation solutions [20], the distributed electricity generation market [21], energy efficiency programs [22], evolution of energy utilities [23], and the ongoing expansion of distributed electricity generation market [24]. As a result, the business model concept has been widely tested in practice in the energy sector. Common components of the business model include the value chain, value propositions, target markets, competitive strategy, revenue-generation models, customer interface, value network, and infrastructure service [18, 25].

### 2.2. Business-model innovation

Business-model innovation as a term remains largely vague. Reference [25] notes that business-model innovation is less a matter of superior foresight, but more of trial and error and ex-post adaptation. Reference [26] suggests that it entails business model experimentation, while [27] views it as a strategic renewal mechanism for organizations undergoing through periods of transformation in their external environment [28]. In this chapter, business-model innovation refers to the development of new organizational forms to create, deliver, and capture value for realizing a distributed utilities future. Electric utilities in New York and elsewhere have different starting points, value propositions, customer expectations (across customer classes), and priorities, and they vary significantly with respect to electricity revenues, electricity sales, and customer-base. How can utilities meet these demanding business expectations in an uncertain environment? Fox-Penner (2010) offers a solution through a "two-and-a-half-business model" innovation as an alternative [13, 28]. The half refers to a smart integrator scenario in which the utility operating the power grid does not own or sell the power delivered by the grid. Consequently, power generation and grid infrastructure development including its information and control systems are community-owned (e.g., a community micro-grid). The advantage of a community-owned distributed generation is its potential for economies of scale. Hundreds to thousands of customers join the network participating as both consumers and producers (or prosumers) of renewable electricity from sources like solar PV and wind turbines. These prosumers use the set operational standards, but the financing and administration side of the business model is handled separately by the utility.

With that in mind, our research shows that aligning core business incentives of electricity distribution utilities with cost-effective integration of DERs into power systems is a prerequisite for achieving DMS and UCM business model constructs that might allow this future to come about, arguing for a 'polycentric' approach in the near term. As a preliminary matter, it is commonly noted that the smart integrator model has well-developed analytic capabilities to ensure the electric grid can meet electricity demand at all times. The smart integrator model also has a green dispatch mechanism that enables utilities to determine when and how to switch to low-carbon energy sources such as solar, wind, and hydroelectric power. Therefore, the only key obligation of the utility is ensuring that the local grid meets power demanded in the system. Second, the smart integrator has a "highly secure but maximally open platform for information, price, and control signals" [13]. This feature ensures that it responds well to different regulatory regimes by integrating information for accounting, billing, and settlement systems to accommodate the more complicated functions such as managing pricing plans, payment, and billing. Related to the smart integrator model is the energy services utility (ESU), which is an extension of the smart integrator model. In the ESU model, the focus of the utility shifts from being a purely asset- and commodity-driven entity to a service and value-added enterprise in which profit achievement hinges on the services offered to consumers [13, 15, 28]. Examples of the ESU business model include programs offered by Arizona Public Service Electric Company (the largest electric utility in Arizona), including energy storage, demand response, and load management.

Under a smart integrator, utilities must consider creating different triads of structure, regulation, and revenue models to facilitate transformation to a distributed utilities future. This process requires a variety of innovations, including joint construction and developments of electricity generation and delivery of electricity services such as financing and building related assets, ownership, and operations; growth of diversified independent transmission companies; diversified of generation mix with high composition of low-carbon resources mostly from natural gas and renewables such as hybrid solar PV systems, polygeneration energy systems, or zero-net energy systems; use of subsidiaries to speed up clean energy diversification; and use of utility consortia that expand member utilities' service offerings beyond the provision of electricity service (e.g., to cater to cooperative customers).

### 2.3. Utility-side versus customer-side business model

Two principal factors concern utilities. First, electricity must get to the customer reliably and safely. Second, power must be delivered efficiently to maximize profit margins. These factors put pressure on struggling utilities to minimize electric grid system losses. Utility-side business models, concepts, components, and technologies therefore ought to take these factors into consideration. With the growth of prosumers, the challenge then becomes: which key policy, market, and business concerns should utilities prioritize? Other salient challenges include optimal deployment of expensive assets, need for diversification of generation, demand response management, grid stability, and tariff implementation. Some of these challenges can be addressed by deploying 'smart' technologies at the utility-side to monitor operations and improve billing and tariff management. In states with fast changing electric utility landscapes such as New York, however, regulators need to identify and deconstructed elements of innovations in a contextually-appropriate manner to assure scalable solutions.

Ref. [29] examines a suite of wholesale power market design currently in use on the customer-side to improve electricity reliability, security, and flexibility. It also assesses feasibility of wholesale market design with high penetration of DERs considering the role of technological innovations such as demand response, distributed generation, and energy storage. These technologies support the infrastructure needed to provide electricity services and address critical challenges such as climate change, energy security, and revenue erosion [2]. The revenue erosion concern can also be addressed through customer-side renewable electricity business models. In this chapter, distributed generation systems refers to small-scale generation systems (e.g., for private customers and small- to medium-sized businesses) in the range of a

| | Customer-side business model | Utility-side business model |
|---|---|---|
| Customer interface | • Better customer relationship needed to develop new value propositions.<br>• Changes in customer segments.<br>• New channels are needed.<br>• Customer hosts energy generation system and shares the benefits with the utility.<br>• Long-term customer relationship. | • Utility-customer relationship remains unchanged.<br>• Customer segmentation leads to increased customer base and "eco" price premium earnings.<br>• Channels remain the same<br>• Electricity is treated as a commodity.<br>• Customer does not host energy generation systems.<br>• Customer pays per unit. |
| Value proposition | • Shift from commodity delivery to energy service provider.<br>• New value propositions needed for the market. | • Bulk generation of electricity supplied to the grid.<br>• Additional energy related services and customer value. |
| Infrastructure | • Large number of small-scale assets.<br>• Generation close to consumers.<br>• Experienced in small-scale energy projects.<br>• Partnerships with system suppliers and local installers. | • Small number of large-scale assets.<br>• Centralized generation.<br>• Experienced in large-scale infrastructure projects.<br>• Partnerships with project developers and suppliers. |
| Revenue model | • Revenue from direct use, feed-in and/or from services.<br>• High transaction costs reduce profit margins.<br>• New revenue models needed.<br>• Complex electric cost structure more due to many small investments instead of few large investments. | • Revenues through feed-in of electricity.<br>• Economies of scale from large projects and project portfolios.<br>• Revenue models are available.<br>• Electric cost structures are in favor of utilities experiences with large-scale infrastructure financing. |

**Table 1.** Utility-side versus customer-side business model.

few kilowatts to about 5 MW from sources such as solar PV, micro-wind turbines, and micro-combined heat and gas-power systems. Accordingly, customer-side and utility-side business models follow a very different logic in the value chain: the former is based on many small projects while the latter focuses on a small number of large projects. **Table 1** summarizes the differences of the two models [30, 31].

Unlocking greater value of distributed utilities requires new business models that improves ownership, asset management, and monetization of utility assets. In the utility-controlled and utility-owned value arrangement, utilities continue to execute their core competency functions, for example, asset ownership and operation. For instance, New York State's (NYS), clean energy standard (CES) provides for a "50 by 30" goal, which commits the state to procure 50% of its electricity from renewable resources by 2030. Each load-serving entity is required to procure for their retail customers renewable energy credits (RECs) linked to DERs listed in Tier 1 (e.g., solar, wind, biomass, and pumped storage hydroelectric) [32]. Likewise, the customer-side structure provides a context in which to situate the RECs' management; utilities can bundle these RECs into service programs, such as utility green pricing plans, and sell them to other parties.

## 3. The Hamel framework for utility business model evaluation

A fundamental challenge facing New York today is how to generate richer innovations at all levels, including products, business models, and management systems that transform a centralized power system into a high-performing distributed utility sector. The critical challenge in this endeavor, however, entails fashioning a comprehensive analytical framework that captures components of business model across the entirety of the market spectrum. To avoid the pitfall of ambiguous strategy in such a framework, a service-based business model approach should be adopted. Ref. [33] identifies six key functions of business model strategy as value proposition, revenue generation mechanism(s), value chain, value network, target market, and a competitive strategy, while [19] lists the four often-cited business model components: strategic resources, value creation, value capture, and value network. Hamel business model [34], which is applied in this chapter, incorporates these fundamental features, providing a robust framework (**Figure 3**) for analyzing the REV vision. It appears that REV is based on a polycentric paradigm as the main pathway with which utility market reorganization will be navigated. Several studies have already explored UCM governance approaches with polycentric characteristics, e.g., [35–39]. These contributions largely focus on bending reality, business model constructs, and institutional and near-term governance as an impetus for polycentric innovation. We argue here that so long as utility regulation and governance lag behind technology innovation, institutional innovations needed to support the industry to "become more adept at generating richer innovations at other levels, including products, services, business models, and management systems," will continue to play catch up thus impeding the full participation of DER resources [40].

Hamel's business model is comprised of four major components (i.e., core strategy, strategic resources, customer interface, and value network), three bridge components (customer benefits, configuration, and company boundaries), and sub-elements that determine the profit potential (efficiency, uniqueness, fit, and profit boosters). The first component, a *core strategy*, is the essence of how a firm chooses to compete. The sub-element, or the business mission, captures the overall objective of the strategy or what the business model is designed to accomplish or deliver. According to the Hamel framework, the business mission defines the decisions of a firm, such as the value proposition, strategic intent, purpose, goals, and overall performance objectives. Therefore, when a company changes its business mission, this does not necessarily imply innovation in business concept.

The product/market scope defines where the firm competes (i.e., the firm's competitive arena). For instance, the scope determines the customers, geographies, and product segments [38]. In this regard, the definition of product/market scope can be a source of business concept innovation for a firm—especially when it is entirely different from that of traditional competitors [34]. Finally, basis for differentiation captures how the firm or organization competes differently from its competitors. For instance, a firm differentiates itself from competitors by seeking answers to questions such as: how do opponents differentiate themselves in the electricity market (e.g., in designing utility revenue models such as platform service revenues, rate design, and customer energy data usage)? Are there other dimensions of market-oriented revenue model differentiations that could be explored? In what aspects of the energy service (e.g., rate design) has there been the least differentiation? How could differentiation be increased in some of these dimensions (e.g., by implementing opt-in rate initiatives such as time-of-use rates or smart home rates)? And have differentiation opportunities been diligently sought in every dimension of the business model?

Hamel's second major component, *strategic or unique firm-specific resources*, constitutes a source of competitive advantage. Fundamentally transforming the market to increase renewable electricity generation in New York is a source of business concept innovation. A successful business model thus creates its own intellectual hegemony. Strategic resources embody core competencies, and comprises skills and unique capabilities. Strategic assets depicts what is owned by the firm. They are rare and valuable things other than know-how, and include brand, patents, infrastructure, proprietary standards, and customer data. A prudent firm-wide use of strategic assets can lead to business concept innovation. According to [41], asymmetry in the resources a firm controls and discretionary managerial decisions about resource development and deployment can be sources of sustainable economic rent. On the other hand, core processes illustrate what people in the firm do. They are methodologies and routines used in translating competencies, assets, and other inputs into customer value. A reconfiguration of central components and core processes in the business model therefore constitutes business concept innovation [42].

The third major component of the Hamel framework is *customer interface*. It is comprised of four elements: (a) *fulfillment and support*, which describes market access (i.e., how the firm reaches the market and it includes channels, customer support, and service levels); (b) i*nformation and insight*, which refers to knowledge that is collected from customers and the ability of the organization to extract insights from this information to design new products and services for customers; (c) *relationship dynamics* refers to the nature of interaction between the firm (producer) and the customers; and (d) *pricing structure* specifies the revenue mechanism for monetizing services rendered (i.e., flat-rate charges or charges based on TOU).

The fourth component is the *value network* of the firm. This includes suppliers, partners, and coalitions that complement and strengthen organization's resources. Suppliers typically reside "up the value chain" from the producer [34]. The configuration of activities is a bridge component that links the organizations' core strategy to its strategic resources. *Configuration* of activities specifies unique ways in which core competencies, strategic assets, and core processes interrelate to support a chosen strategy and how those linkages are managed in order to achieve greater value. Intermediating between the core strategy and customer interface is another bridge component—the *customer benefits*—which describes the bundle of benefits that is essentially offered to consumers. *Company boundaries* refers to decisions regarding what the firm does internally based on what it contracts out to the value network.

At the base of the framework are four factors that define the utility of the Hamel business model. *Efficiency* guarantees that the value of benefits delivered to customers exceeds their

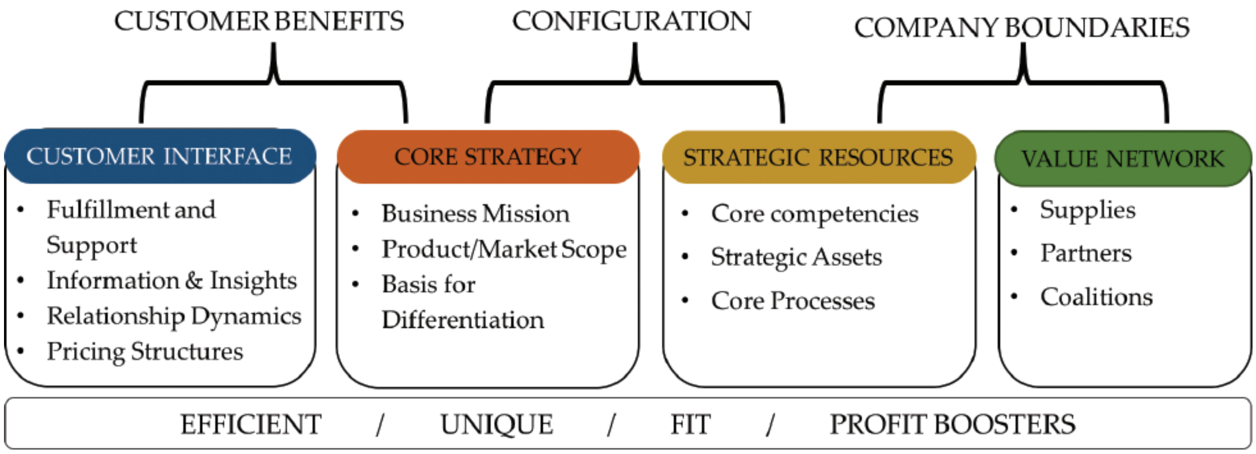


**Figure 3.** Components of Hamel business model framework.

production costs. *Uniqueness* demonstrates the level of convergence among business models in terms of conception and execution in ways that add valued to customers; the greater the convergence among business models, the lower the potential for above-average profits. *Fit* means that all the elements of the business model are consistent and mutually reinforcing, and that all the parts work together for the same end goal. Finally, *profit booster(s)* include increasing returns, competitor lock out, strategic economies, and strategic flexibility. Positioning the Hamel business model as the unit for analysis of market reorientation in electric industry thus provides a robust and multi-dimensional framework for evaluating the suitability of new proposals for electric utilities and energy governance in in New York.

## 4. Evaluating the REV docket: the détente for utilities and DER

Initiated in 2014, New York's REV program is a comprehensive effort to reform the state's energy system in order to align ownership, management, and operation of its utility industry [43, 44]. REV is led by NYPSC and seeks to fundamentally transform the electric power sector of New York State from a primarily centralized generation system to distributed utilities model [45]. The REV docket has two tracks. Track 1 focuses on the development of DER markets and the utility-as-platform model known as distributed-system platform (DSP) providers, while Track 2 focuses on reforming utility-ratemaking practices and revenue streams to accommodate the proposed DSP model. Implementation of REV will take several years and will involve the mutual efforts of industry, customers, non-profit organization, and regulatory partners. The initiative encourages regulatory changes that promote energy efficiency, demand response, increase storage capacity, and increase renewable energy resources. These reforms empower end-users by providing more choices through diversification of energy resources, and by fostering improvement in the performance of the power sector across policy objectives such as system-wide efficiency, system reliability and resiliency, enhanced customer billing system, market animation and leverage of customer contributions, fuel and resource diversity, and reduction of carbon emissions [44].

Richard Kauffman, chair of the state's Energy Research Development Authority (NYSERDA) and former NYPSC Chair Audrey Zibelman explain that the REV program is "removing market barriers and bridging market gaps that have historically impeded the clean energy sector from benefiting from technological innovations" [46]. Its major impact on the industry so far has been increased integration of solar- and wind -energy generations. Therefore, this evaluation focuses on the regulations and directives specified by the NYPSC, and other guidelines released by key power utilities in the state [e.g., Consolidated Edition, Long Island Power Authority, Niagara Mohawk Power Corporation, New York Power Authority (NYPA), New York State Electric and Gas Corporation (NYSEG), Central Hudson Gas and Electric Corporation (CHGEC), Orange and Rockland Utility Inc., and Rochester Gas and Electric Corp (RG&E)] to explore the characteristics, nuances, structure, and approaches applied.

### 4.1. From centralized models to distributed system platforms

Retail peak electricity demand in NYS is approximately 75% greater than the average system load, and nearly 9% of power generated in the state is lost in transmission [47]. Essential investment needed through 2025 to replace the state's aging infrastructure to meet projected energy demand is estimated at $30 billion [43]. REV is thus a 'polycentric' strategy intended to make distribution planning more transparent and better integrated. For instance, it seeks to transform electric distribution companies into DSP providers with responsibility for active coordination of DERs. It fosters "transactive energy" ecosystem in which "consumers and other parties can take full advantage of every type of energy resource—on both sides of the meter" [45]. Key to this ambitious goal is reorienting the traditional regulatory model by aligning utility and consumer interests so that both groups benefit from (scalable) improved market efficiency and scalable organizational learning.

Two pricing mechanisms offer a critical role in this regard. First, REV establishes benefit–cost analyses as a foundational procurement tool to determine renewable electricity deployment [48]. Chosen due to its regulatory familiarity and apparent simplicity [49], the multi-year distribution system integration plans (DSIPs) to be developed by utilities seeks to foster a fair, open and value-based decision-making environment for utilities to build out their own competitive advantage in the DER market [45]. The benefit–cost approach will be applied in DSP investments, procurement of DERs through competitive selection and tariffs, and energy efficiency programs. Second, REV proposes using locational marginal pricing (LMP) principles to optimize the value of distributed utilities. Application of LMP principles can help distinguish which configuration of distributed resources enhances system flexibility and yield overall best value to consumers [44]. In terms of a repurposed DER policy, market development, innovation in designing value strategy and benefit–cost of DSIPs, and investment in community-choice aggregation programs, the REV model shares some of these characteristics with other ambitious and successful initiatives, particularly the German Energiewende initiative [50]. New York is not alone in its efforts to improve its utility regulation market and optimal system efficiencies. Parallel regulatory actions have been proposed in California, Hawaii, Massachusetts, Minnesota, and Illinois through its proposed utility of the future study known as "NextGrid" [51]. However, REV represents the most promising utility-as-platform business model as it challenges two fundamental components of the conventional utility model: the assumption that electricity demand is inelastic, and the notion that economies of scale make a centralized generating model the most economical way for electricity services provision [52] and market development. **Table 2** summarizes the main policy, regulatory, and technological solutions that utilities and planners have proposed to improve DMS and UCM strategies based on polycentric approach to business-model innovations.

### 4.2. Application of the Hamel Framework to the REV Docket

**Table 3** offers a four-part, multi-dimensional, Hamel analytical framework and application of the key dimensions to REV. These dimensions extend beyond business-model innovation in the utility industry. These dimensions attempt to account for the increasing focus on performance-based utility operation, the relationship dynamics that accompany such a shift [58] and the required transition to a servitization system—as mandated by system reliability and resiliency, system-wide efficiency, and the climate change challenge [3].

#### *4.2.1. Strategic resources and opportunities: utility assets*

There are four main types of electric utilities in NYS, namely investor-owned private utilities, retail-power marketers, state-owned public authorities, and municipal utilities. These utilities can be grouped into two service types: bundled and delivery. Several organizations have institutional capabilities, mandates, and responsibilities for managing utility customer choice archetypes in New York (**Figure 4**). Eventually, NYSERDA may emerge as the hub of such polycentric activities. However, a more polycentric governance approach could potentially emerge across and between several bodies as institutional innovation takes root, with organizations such as the NYPSC and FERC providing oversight mechanisms for greater transparency in utility rate design, wholesale market regulations, and DER integration, and organizations like the North American Electric Reliability Corporation (NERC) and New York State Reliability Council (NYSRC), establishing greater degrees of reliability standards. This polycentric innovation development could help minimize information asymmetries and

| Policy, regulatory, and technological solutions for advancing polycentric innovation | Author(s) |
|---|---|
| Information asymmetry, capital expenditure bias, and time-varying rates. | [53, 54] |
| Distribution utilities and their place in an integrated grid model to provide infrastructure services, enhance personalization, and value creation. | [1] |
| Energy performance contracting, regulation of retail energy markets, and innovation of revenue and pricing models. | [16, 55] |
| DERs, DSPs, benefit–cost analysis framework, and net energy metering. | [3, 55, 56] |
| Institutionalized polycentric innovations in energy governance, and sociotechnical co-evolution of energy planning and policymaking. | [10, 38, 39] |
| Marginal-cost-based dynamic pricing and time-varying electricity rates. | [47] |
| Utility financial incentives, investments, utility of the future roadmaps: (smart grid development, DERs, and customer utility service model). | [45, 57] |
| Electric grid modernization and polycentric governance (democratized energy paradigm). | [45, 46] |

**Table 2.** Policy, regulatory, and actions for polycentric innovation.

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| Component | Definition | REV features |
|---|---|---|
| Strategic resources | Depicts the architecture of the utility value creation. Includes strategic assets, know-how, core processes and competencies. | An estimated $30 billions of investment in the state's aging grid infrastructure is required by 2025.<br>NYSERDA's Clean Energy Fund provides $5B investment in new green energy over 10 years, starting in 2016. |
| Customer interface | Greater customer interactions, including customer relationship, segmentation, fulfillment support, and revenue structure. | REV promotes greater consumer choice.<br>Emphasizes enhanced customer-centric paradigm (e.g., billing solutions for effective management).<br>Nonlinear transactions. |
| Value network | Includes utility added values or business offerings to resource providers, suppliers, and partners. | Removes market barriers and promotes distributed utilities.<br>Promotes greater interaction among DSPs to create a market pricing platform, and service monetization. |
| Core strategy | The utility's capacity to change course in the face of potential existential business model risks.<br>This capacity is influenced by the flexibility and complexity of both the business model but also the infrastructure it operates. | Distribution utilities act as DSPs.<br>Energy efficiency savings are part of utility revenue not dedicated surcharge.<br>Earning impact mechanisms (EIM) replace platform service revenues (PSR) and market based earnings (MBE).<br>Includes modified clawback mechanisms to attract third parties.<br>Encourages time of use (TOU) rates.<br>Each utility submit benefit–cost-analysis plan. |

**Table 3.** Application of Hamel business model to conventional energy utility.

strategic behavior such as disguising true expected future costs to the regulator to increase allowed revenues or returns. As the NYPSC contends, "asymmetry regarding system information if continued will result in a barrier to new market entry by third parties and ultimately impede innovation and customer choice" [44]. On the other hand, New York Independent System Operator (NYISO)—a non-profit organization set up by NYS—could emerge as the central open platform for procuring DERs from suppliers. NYISO currently administers wholesale electricity markets in the state and provides reliability planning for bulk-electricity power, but this function could expand with the growth of DERs especially bulk power generation. Ultimately, NYISO would continue to oversee the wholesale electricity markets in NYS while FERC regulates wholesale electricity rates, licenses hydroelectric projects, and sets policies for interstate electricity sales. Under FERC Order 745, FERC regulates wholesale product tariffs by independent system operators (ISO) such as NYISO—including integration of DERs into wholesale markets [45].

The state's strategic resources and utility assets are owned, operated, and regulated by a variety of private and public entities (**Figure 4**). The functions provided by this complex electricity infrastructure create a path dependency in which existing business models either enable or constrain energy market development. The resulting utility landscape that manages the flows of all these energy resources has experienced consolidation to the point at which, in 2015, a "baker's dozen" of three holding companies (namely Consolidated Edition, Long Island Power Authority, and Niagara Mohawk Power Corporation) representing 2.4% of all integrated utilities controlled 49% of utility revenues [4]. The REV model fully addresses the subcomponents of strategic resources (core competencies, strategic assets, and core processes) of the utility industry such as the aging infrastructure challenge. It supports what Reference [59] refers to as "infrastructure to services transition", or the "evolution of infrastructure for commodity delivery" to support greater personalization of value—new purposes, new platforms, enabled new infrastructure, and new applications (services).

*4.2.2. Customer interface: increasing customer choice and control*

REV empowers customers with meaningful level of choice and reduces cost-of-service of electricity consumption. For instance, it improves electricity billing system and knowledge of customer analytics, and animates the market with substantial choice offering about the consumption and provision of electricity services (e.g., from whom to procure electricity services and from what resources) [45, 46]. Conventional electric utilities compete by establishing utility-consumer relationship characterized by billing-based interactions that are impersonal, distant, and standardized. This distant aspect arises partly due to primary fiduciary obligation

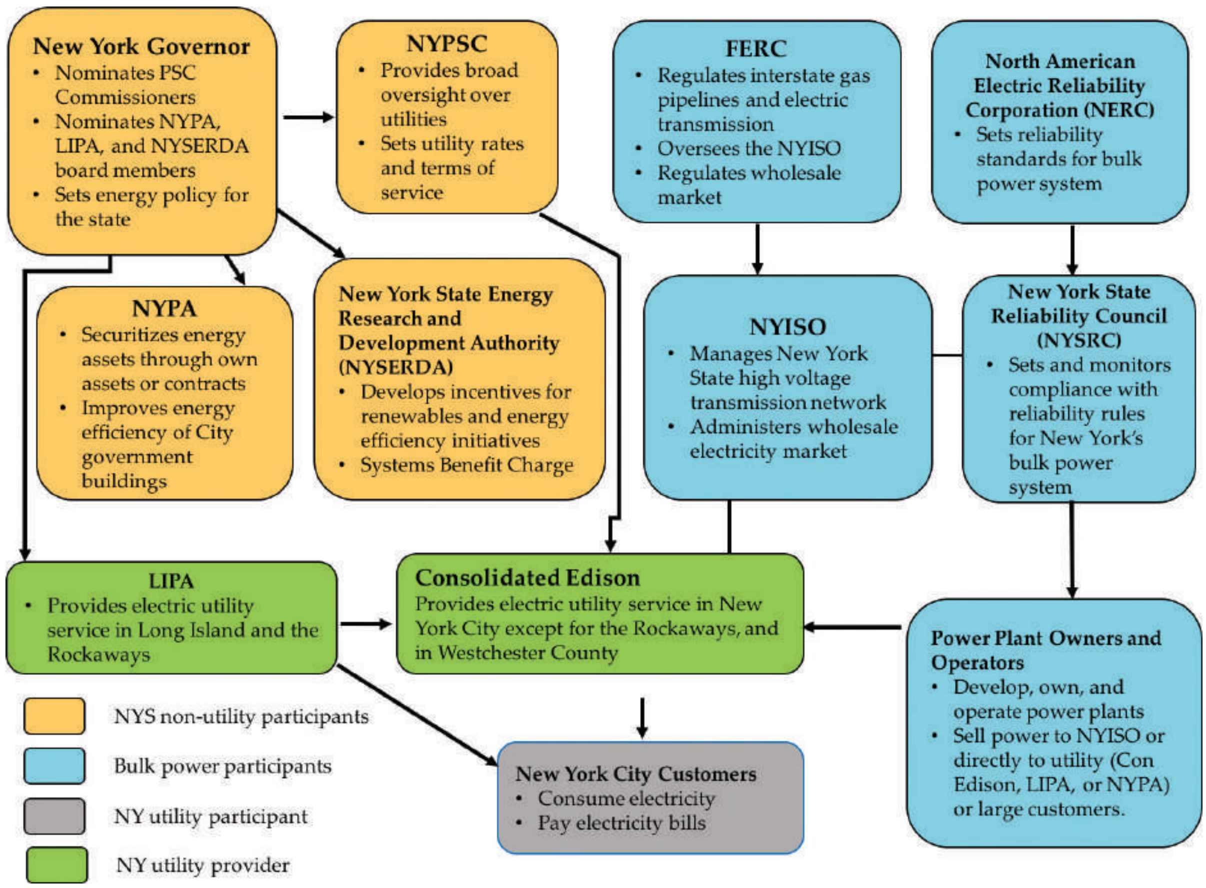


**Figure 4.** NYS electric industry participants and institutions.

to the owners and shareholders of the company. Additionally, conventional utilities are characterized by less customer interactions as they do not go "beyond-the-meter."

Fundamental to optimizing behind-the-meter storage assets and DERs like rooftop solar is sharing of distribution-level data of the utility grid and common understanding of its distribution system. In 2015, a total of 124 utilities operated in New York with investor-owned utilities accounting for 12% of the total market share, representing 71% of customers (**Figure 5**). Behind the meter, cooperative, municipal, retail power marketer, and state utilities accounted for 9.7, 0.8, 9.7, 65.3, and 2.4% of the total market ownership, respectively. Investor-owned utilities operate under conditions of a guaranteed rate of return that is set by NYPSC. In the conventional business model, utilities invest in large-scale asset, economies of scale, and long-term infrastructural commitments that determine the form of the revenue/cost structure. These features still influence portfolio of electricity sales, revenues, and customer numbers of certain utilities in New York, even as the implementation of the REV model is ongoing. Behind-the-meter recorded the fastest growth in electricity revenues, sales, and customer count of 89.4, 78.6, and 68.7% in 2015, respectively. Under REV, DSP providers "create markets, tariffs, and operational systems to enable behind the meter resource providers to monetize products and services that will provide value to the utility system and thus to all customers" [43].

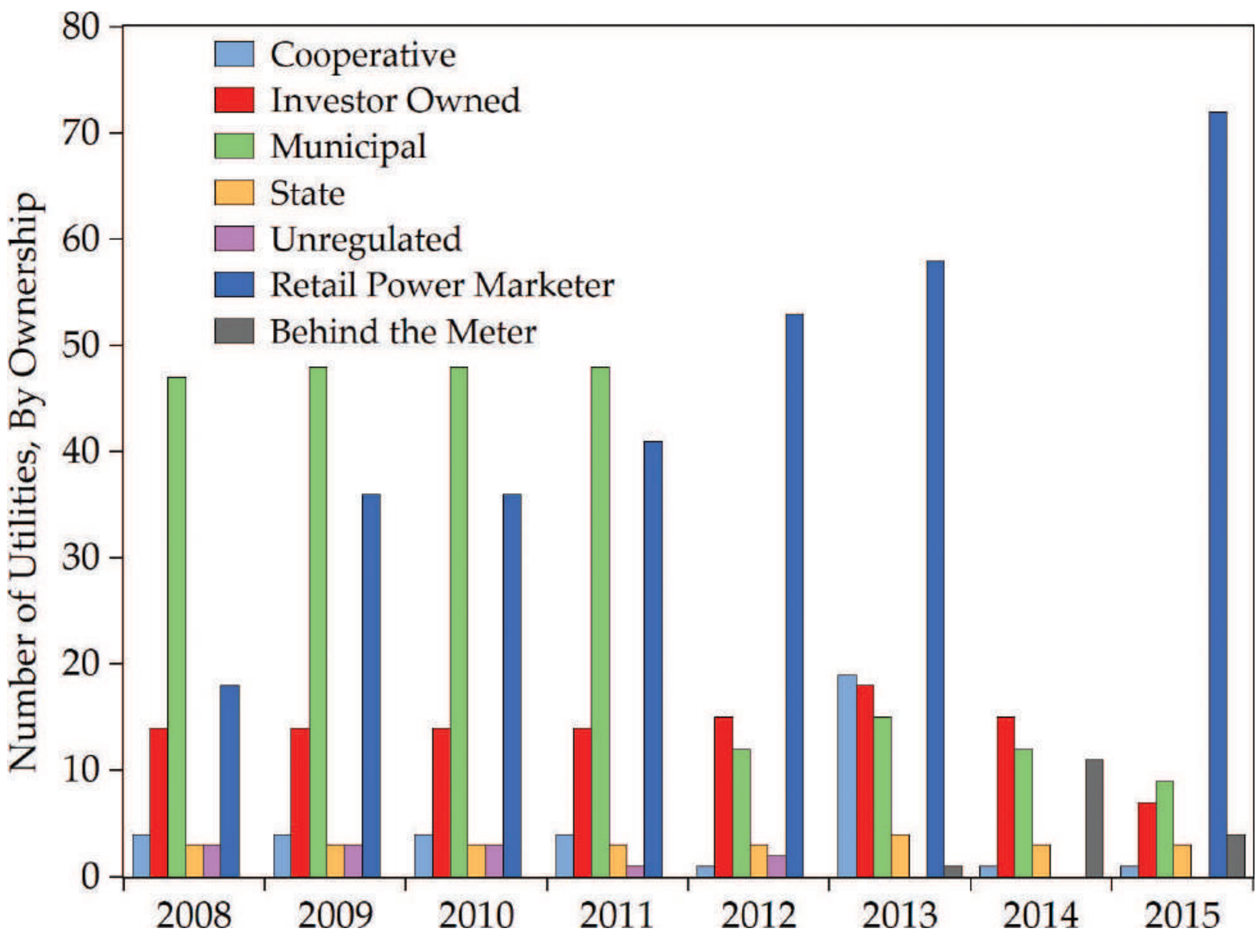


**Figure 5.** Number of utilities, by ownership from 2008 to 2015.

*4.2.3. Value network: expanding customer-base*

The business model of the traditional utility pursues expansion in asset-based and, through its commodity-focused strategy, increases shareholders value. The goal of the conventional utility, as such, can be conceptually positioned at one end of a profit-motivation spectrum: the "motivation to build incremental assets for the primary purpose of expanding its rate-base" [60]. Because regulators reward or chastise utilities for decisions to achieve certain public-policy goals and to maintain "just and reasonable revenues," this model faces mounting challenges—especially in a DER framework. So-called "incentive regulation," however, establishes the working conditions of the utility. Within these conditions, "[g]iven any set of regulations, utilities participate in actions which most benefit their principal constituencies—shareholders and management—while meeting the requirements of the regulations" [61]. Because the principal constituency of the investor-owned utility is its shareholder base, REV seeks to expand utility customer-base through *value addition* to scaling economic efficiency.

*4.2.4. Core strategy: animating business-model innovation*

All the major distribution utilities in New York support the REV vision for long-term innovation in the industry and have submitted proposals for pilot projects. Additionally, a number of utilities have began implementing "flexibility products and services" such as distributed solar PV inverters, real-time transactions, demand response, and pricing of reserves that would enable them to obtain electricity from the most flexible resources. Response to these market changes, however, depends on adaptations in the utility regulatory landscape. Nevertheless, the dependence of the modern society on a stable and reliable electricity system require that these innovations should be ongoing throughout the lifetime of the electricity grid infrastructure.

The transition from centralized to decentralized renewable electricity governance animates business-model innovations to address "death spiral" concerns and inefficient resource allocation. REV's core strategy addresses market risks in New York by increasing DER deployment, increasing transparency in utility ownership, incentivizing low-carbon electricity generation, and aligning utility profits with DER deployment [45]. However, as [36, 62] caution, these innovations must not be construed as attempts at regime preservation rather than market adaptations for fostering 'polycentric' business-model innovation. In other words, the REV docket's core strategy positions political and economic innovations of the utility landscape to optimize customer-focused operations and return on environment. For instance, the role of the ESCOs which currently provide only commodity services (e.g., energy efficiency investments) are expanded to include more classes of electricity services including consulting and analytic services to help consumers dynamically manage their energy bills.

## 5. Conclusion

The key objective of this chapter was to evaluate the viability of the Hamel business model and its application to evaluating the New York's REV vision and the state's path for optimizing distributed energy future and customer choice. The Hamel framework proved to be a valuable analytical business model methodology in this context. The chapter reveals that residential and commercial rooftop solar electricity generation systems is expanding in

New York led by behind-the-meter facilities producing power intended for on-site consumption in homes, office facilities, and commercial buildings. Our findings show that New York utilities are increasingly investing in behind-the-meter renewable energy projects. Utilities favor these customer-side projects which recorded the fastest growth in electricity revenues, sales, and customers in 2016 of 89.4, 78.6, and 68.7%, respectively.

The chapter sheds lights on the growing influence of business-model innovations and the New York's REV docket in optimizing utility customer choice management and distribute system planning of electricity services. This research shows that implementation of the REV vision in a polycentric fashion offers significant benefits to all customers, not just those that subscribe to them, by generating richer innovations in pricing plans, consumer choice management, and customer analytics to improve utility operations and customer satisfaction. The expansion of renewable electricity market in New York would be impossible without support from state and federal policymakers. Although key polices and market regulations including community choice aggregation, net metering, clean energy fund, dynamic load management, low income affordability, and utility energy efficiency proposals have been proposed and even in some cases implemented in NYS to improve the development of distributed utilities and services, significant improvement in regulatory and market reforms is still required to eliminate market, financial, and economic barriers and skewed incentives that presently impede the efficient evolution of the utility sector. One of the key market development needs is thus to emphasize heavily improvement in the utilities' business-model innovation through external partnerships and suitable organizational structures that promotes an integrated renewable electricity utility market statewide.

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## Conflict of interest

No potential conflict of interest was reported by the authors.

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# Energy Resources in Agriculture and Forestry: How to be Prepared for the Internet of Things (IoT) Revolution

Cleonilson Protasio de Souza and Orlando Baiocchi

Additional information is available at the end of the chapter

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**Abstract**

The Internet of Things (IoT) revolution is getting attention of all kinds of enterprises and industries: from the big ones to the startups. From the energy point of view, deploying IoT devices in urban or industrial environments is not a dramatic problem since electrical outlets and chemical batteries are easily available almost everywhere. However, why not tap into natural resources first? The future may bring an Internet of Natural Things (IoNaT). If so, the agricultural and forestry industries will certainly take advantage of such technology. The question will then be how to power the IoNaT. Chemical batteries are not an environment-friendly option in an agricultural field or in a forest. In this chapter, we suggest different and innovative, natural and easily available energy sources and the main processes to harvest them. The use of these natural and revolutionary technologies may ensure that monitored data could be obtained in a sustainable way.

**Keywords:** internet of things, energy harvesting, environment-friendly energy sources, chemical batteries, internet of natural things, wireless sensor network

## 1. Introduction

Currently, the expression Internet of Things or simply IoT has been broadly used. However, the actual meaning of IoT, in the sense to help to understand how it could change the world, could be extracted as compared to the Internet revolution.

The Internet revolution was the development of a global network where data are originated by people (typing, pressing a record button, taking a digital picture or scanning a bar code) using connected computers [1, 2]. For its turn, the IoT revolution has its premise that any object or thing (like a light lamp, a door, a refrigerator, a garment, etc.) can directly originate and send data to the Internet without any human interaction. For example, a sensor in a connected light lamp may automatically order a new one when it is near the end of life. In short, the Internet is based on human-entered data and the IoT on Thing-entered data.

As the world population is estimated to reach 8 billion by 2020 and supposing that each individual may be related to about five different connected Things[1], we can compute 40 billion of connected Things by this time. However, the IoT revolution does not relate only to people, but all kinds of enterprises and industries (e.g., all products of a given industry may be connected). In this sense, that number could reach trillions.

From the energy point of view, deploying IoT devices in urban or industrial environments is not a dramatic problem since chemical batteries are easily available and electrical outlets are almost everywhere to recharge them.

Nevertheless, it is important to highlight that this huge number of connected Things would need batteries to work and, more importantly, chemical batteries wear out, even the rechargeable ones, and, if not properly disposed, they can be harmful to the environment.

From the point of view of urban life, IoT is an extraordinary technology despite the chemical batteries issue where massive recycling campaigns worldwide or even recycling laws can minimize its damage to nature.

From the point of view of non-urban life, as rural, forest and other natural environments, the IoT will certainly be a very interesting technology. We have to be carefully prepared to take advantage of such technology because it could be hard or impossible to take back batteries for recycling from battery-powered IoT devices deployed directly into the environment.

From this perspective, the future may bring an Internet of Natural Things (IoNaT). For example, a Thing could be a tree, a fruit, a submerged stone in a river, etc. However, IoNaT presents some challenges as radio frequency (RF) communications in the presence of vegetation and powering the electronics of the Things using batteries. Considering the battery issue, deploying them directly into the nature is certainly not an environment-friendly option. The question is how to power the IoNaT using a non-battery approach.

In this chapter, we suggest different and innovative natural, easily available, energy sources and the main processes to harvest them. The use of these natural and revolutionary technologies may ensure that monitored data could be obtained in a sustainable way.

## 2. Batteries, problems, and solutions

Batteries have played an important role for decades both in small-scale energy storage and in high-scale energy storage. For small-scale (e.g., video/audio players, medical equipment,

[1]Connected Things: an IoT-device connected to the Internet.

power tools, meters and data loggers and remote sensors), batteries enable portable use [3] and free the device from power cords and also from being near to an energy power socket. However, the batteries in these devices are discharged and then recharged periodically, meaning that the portability feature takes the fixed costs of replacement or of recharging as a disadvantage.

> *Nevertheless, batteries do not free the device users from power cords since they still need them to connect the battery charger to energy power socket. In this sense, charged batteries works as an invisible cable or, better, as an energy transportation system since the energy source is distant from the device. Ever the most modern wireless charging station based on Inductive Power Transfer* [42] *need its base to be plugged to an energy power socket.*

Batteries are devices that convert the chemical energy contained in their active materials, immersed in an electrolyte solution, directly into electric energy by means of electrochemical oxidation–reduction (redox) reactions [4]. They come in two different forms, namely, disposable or primary batteries and secondary or rechargeable batteries [5]. The reactions are reversible in secondary batteries so that discharging the batteries returns the electrodes to their pre-charged states [5].

Many different battery chemicals are used as active materials, namely, lead, nickel, cadmium, lithium, zinc, manganese, mercury, and others and as electrolyte, namely, acid, potassium hydroxide, organic carbonates, and others [4, 5]. In addition, it is important to observe that electrolyte can be in liquid, gel (which means that it can leak) and solid form [4], and those batteries are packed in metal and plastic cases or containers.

All parts of a battery, as shown in **Figure 1**, are made of pure or compound chemical material where some can be toxic, environmentally unfriendly, or not sustainable. As a result, if batteries are not properly disposed, then their toxic material can leak and contaminate the soil and water, and some of the materials can accumulate into the surrounding environment. Some of these materials can also contaminate humans and the wildlife.

Researchers are continually inventing lower cost and longer life battery chemistries and as batteries become integral part of high-volume products, economies of scale will reduce costs [3]. However, splitting the battery market into small-battery and of large-battery relating it to the IoT industry and the electric vehicle (EV) industry, respectively, it is expected between 22 billion and 30 billion of connected devices ("Things") by the year 2020 [7] and, for electric cars, it may achieve globally between 9 million and 20 million by the year 2020 [8]. That means that billions or trillions of small-batteries and millions of large-batteries will be manufactured, deployed and the wasted ones may be dumped on the nature if not properly recycled. The worst scenario may be one of the IoT worn-out batteries, since the electric vehicle's wear-out battery regulations tend to be extremely rigorous with the carmakers holding responsibilities for them, which differs from the IoT scenario, where responsibility holds on individuals.

In order to show a fair comparison between the IoT and EV battery scenarios, we can normalize the expected number of batteries by the year 2020, using the standard 18,650 cells as normalization base. That is a standard type of Li-ion ($LiMn_2O_4$) battery where 18 indicates that the cell has a diameter of 18 mm, 65 indicates the height of the cell is 65 mm, and 0 indicates

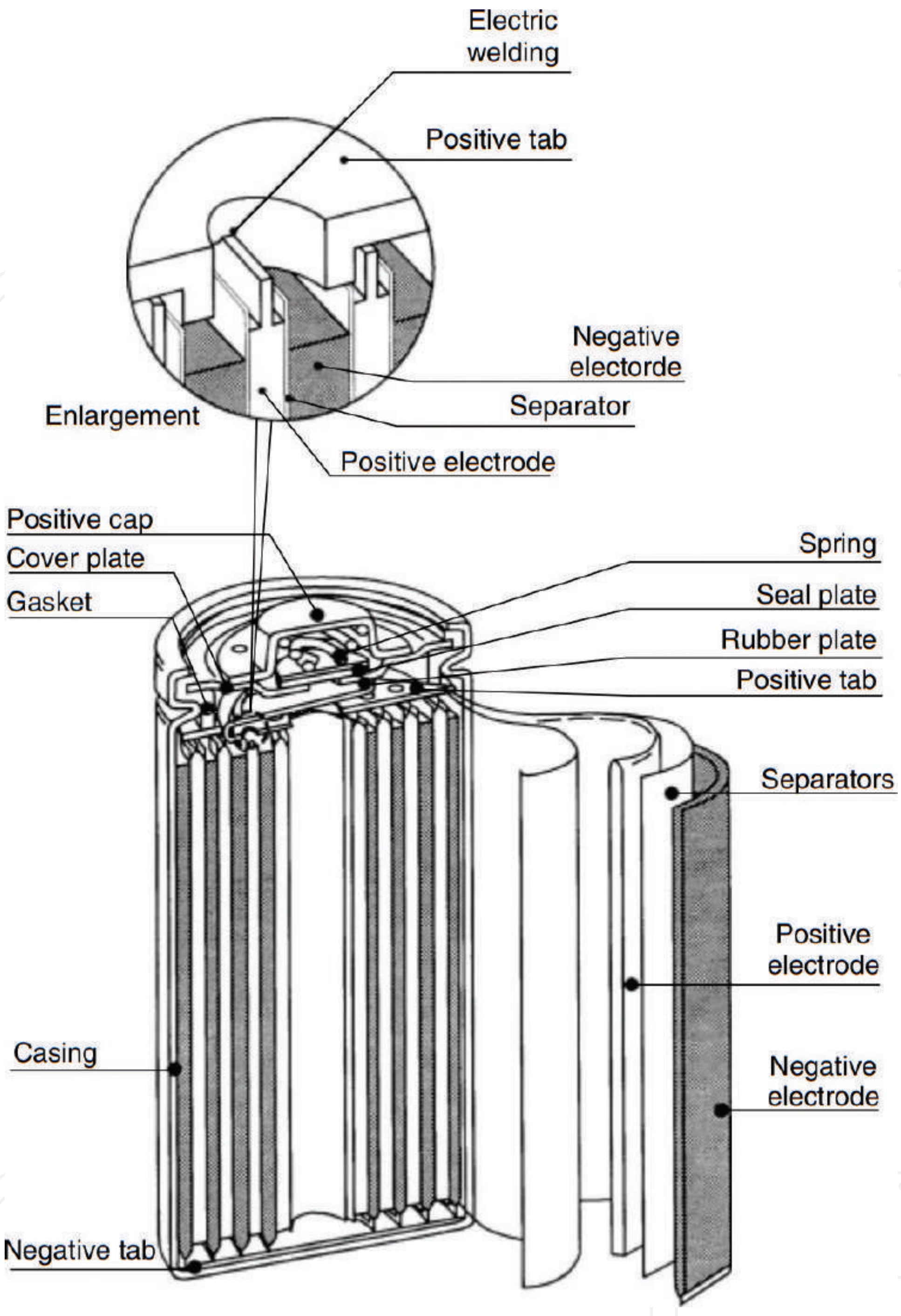


**Figure 1.** Internal structural design of a cylindrical Ni-cd battery [6]. Copyright Wiley-VCH Verlag GmbH & co. KGaA. Reproduced with permission.

the cell is a cylindrical battery [9]) and considering, as an EV default battery size, a battery formed by 6831 18,650 cells. That is also exactly the battery used in the luxury Roadster introduced by Tesla Motors [10].

In this way, it is expected between 3.2 million and 4.3 million of EV-battery-equivalent connected devices by 2020 at which means that IoT battery impact is about 25% of the EV battery

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impact on the environment. As a result, we can consider that the IoT battery scenario has to be considered as harmful to the nature as well as the EV batteries.

An actual solution for this issue is to eliminate the need of batteries of IoT devices generating their energy on the spot where the devices are. Such a solution is theoretically simple, but in practice it needs lots of scientific and technological researches. For instance, how to power an IoT in the middle of an office or on a street? That is where the development of energy harvesting system takes place.

## 3. Energy harvesting

In general, to harness energy from the environment is not a novelty, for instance, solar and wind energies are harnessed for centuries. Despite harnessing energy to high-power applications like industries and cities, which wind and solar power plants are good examples, harnessing energy to low or ultra-low-power applications gave rise to the expression "Energy Harvesting."

Energy harvesting is defined as the process of capturing very small amounts of energy from naturally occurring energy sources surrounding the low-power electronic device to be powered, accumulating, storing and converting them to electrical energy for powering the device [11–17].

> *The possibility to harvest energy from the environment to power electronic circuits became a reality due to the advanced in microelectronic technologies that occurred during the last decades. With this advance, the size of electronic devices has becoming so small, make possible the development of tiny portable devices integrated in objects like watches, glasses, clothes, etc., as well as the energy needed to power these devices has decreased drastically* [16].

Some possible energy sources can be solar light, thermal, mechanical vibration, electromagnetic waves, and so on. For example, a wireless seismic sensor powered by solar cells was the first to be installed in a bridge in Corinth, Greece [17]. Another example, bridges vibrate when vehicles travel over them, and such vibrations have a kinetic energy that can be used to generate electricity [4].

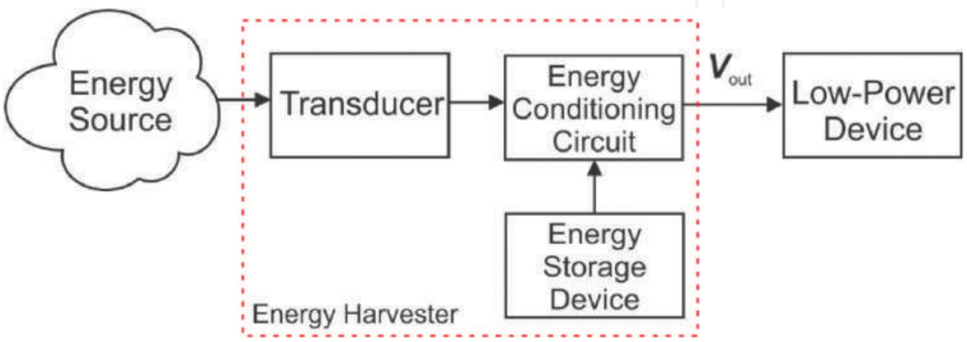


**Figure 2.** Basic structure of an energy harvesting system.

Naturally occurring energy sources can be roughly classified as **environment energy sources** and **human energy sources** [16]. Examples of human energy sources could be kinetic energy coming from arms and legs movements, and thermal energy used to power wearable sensor [18, 19].

Nevertheless, there are some energy sources for energy harvesting applications that occur not precisely naturally, like those originated by electrical, magnetic, and electromagnetic fields, but they can be available in the environment. For example, radio frequency (RF) signal are being harvested to power sensor at a distance [20]. RF energy harvesting is become a good option to power IoT devices.

**Figure 2** shows a basic structure of an energy harvesting system. Its main blocks consist of:

I. **Energy transducer**: it performs the conversion of a primary energy source to electrical energy. Examples: solar photovoltaic cell, in which electrical energy is obtained from solar light energy, thermoelectric generator (also called Peltier module), in which electrical energy is obtained from the difference of temperature on its sides (thermal energy), and so on.

II. **Energy conditioning circuit**: a group of subcircuits, which is capable of adjusting the voltage from the transducer in an adequate voltage for powering the target low-power device. Some subcircuits are rectifiers, filters, DC/DC converters, and so on.

III. **Energy storage device**: it stores energy for two basics, namely: to accumulate energy which is enough to power the target device and to store the surplus energy. The main examples are batteries, capacitors and supercapacitors.

IV. **Low-power device**: the target low-power device.

Utilizing energy harvesting systems as main energy sources is turning to be one of the most promising systems for batteryless low-power electronic devices. However, energy harvesting systems can be combined to batteries (or other energy storages) as a solution to reduce the battery's lifetime limitations or to decrease the dependency of battery performance [21, 22].

| **Energy harvester** | **Power density** |
|---|---|
| Solar panel (outdoor conditions) | 10,000 $\mu W/cm^2$ |
| Thermoelectric generator (30° C) | 3500 $\mu W/cm^2$ |
| Shoe inserts | 330 $\mu W/cm^2$ |
| Mechanical vibrations | 200 $\mu W/cm^3$ |
| Batteries (non-rechargeable lithium) | 45 $\mu W/cm^3$ |
| Solar panel (indoor conditions) | 10 $\mu W/cm^2$ |
| Ambient Radio Frequency | 1 $\mu W/cm^2$ |

**Table 1.** Power density of different energy harvesting propositions [15, 23].

In order to compare and to obtain a general view of different energy harvesting propositions, **Table 1** shows the power density achieved by them.

## 4. Internet of natural things

Even though IoT has gotten substantial attention recently and is a key factor in several paradigms like Smart City [24], Smart Building [25], Connected Cars [25] and Industry 4.0 (Smart Factory) [26], it does not have a standard or globally accepted definition.

Below are some of the concepts related to IoT, which are described taking into account considering:

- **The Thing itself**: A **Thing** (also called smart object) is any object with embedded electronics (microcontrollers, transceivers for digital communication, sensors, actuators, networking processing support circuits, etc.) that can transfer data over a network—without any human interaction [27]. Things can be home appliances, surveillance cameras, monitoring sensors, actuators, displays, vehicles, smart phones, tablets, digital cameras, doors, windows or literally any object that turned into a smart object.
- **The network of Things**: IoT is a communication paradigm that envisions that objects of everyday life, turned into a smart object, be able to communicate with one another and with the users, becoming an integral part of the Internet [24].
- **Service provider**: IoT is characterized by its pervasive nature, meaning that it can be everywhere, enabling nonhuman direct interaction with a wide variety of everyday things and fostering the development of a number of applications. Those applications can make use of the potentially enormous amount and variety of data generated by such Things to provide new services to citizens, companies and public administrations [24].
- **Human benefit**: IoT has as its ultimate goal to create benefits for human beings, where smart objects around people know what they like, what they want and what they need and act accordingly without explicit instructions [28] and to promote an enhanced level of awareness about the world [29].

Taking into consideration the abovementioned concepts, then the IoT can be defined as a network that links smart objects (Things) worldwide, which are capable of: processing, sensing, actuating and communicating with one another, originating directly data to the Internet without any human interaction and providing services to citizens, companies and public administrations.

As described at the beginning of this section, several paradigms related to "smartization" in a given context (e.g., Smart City, Smart Building and Smart Factory) is taking place in the word. In this perspective and considering that the current environmental issues of the planet, it is very natural that the IoT revolution addresses these issues. Consequently, new paradigms as, for example, Smart Forest, Smart Plantation and Smart Farming arise and, as a result, Things can be trees, stones, submerged stones or floating logs in a river, fruits or their fruit trees, barns, cows or anything in a natural or rural environment.

In this context, an Internet of Natural Things (IoNaT) takes places for rising smart natural or rural environments.

IoNaT can be defined as a network of natural Things capable of communicating each other and directly originating data to the Internet and providing services to benefit their environments.

A very interesting example could be a Smart Forest where a Smart Tree communicates with other trees. For example, if its temperature is too high (indicating possibly a fire), these data are passed throughout the network to a nearby fire department or the surrounding neighborhoods.

> *Since 2000, on average, 18 firefighters have died each year fighting flames and the 2015 wildfire season was the costliest on record, with $1.71 billion spent to fight the blazes, as said by the U.S. Forest Service. One of the worst problem battling wildfires is to not know rapid weather condition changing, as for example, wind direction, which can put fire towards firefighters giving no way they get away to a safe position. Therefore, having information about local weather and environmental conditions can save many lives.*

The main challengers for an IoNaT are:

**I.** Power supply to the Things without chemical batteries and

**II.** Communications support in the presence of vegetation.

### 4.1. Energy harvesting as a solution for power supply in the IoNaT concept

Over the last decades, due to the advancement in microelectronic technology, electronic devices are progressively getting smaller and achieve extremely low-power consumption enabling the design of energy autonomous systems (EAS), which are low-power systems that run without being connected to any power grid and are powered by small batteries [30].

In its turn, energy harvesting system either increase the battery's life cycle toward perpetual EAS [14] or marking self-powered batteryless EAS.

Therefore, with the purpose to avoid deploying the battery directly into the nature, the development of batteryless energy harvesting devices is an ideal alternative since they can be designed considering natural energy sources around the natural Thing in the IoNaT context.

Potential candidates of natural energy sources for batteryless energy harvesting devices could be:

- **Solar light**. Everywhere in natural environments as fields, deserts, water's surface, mountains, etc., solar light is a good option with the usage of small photovoltaic cell. However, at daylight, it works well, but at night, it needs some energy storage device to work where capacitor or supercapacitor may be used.

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- **Thermal sources**. In natural environments, this kind of energy is largely available since different materials or substances in these environments when near each other may produce different temperature levels providing a way to obtain heat. For example, under the soil, the temperature can be colder than above, so an energy harvesting solution may take place. Another example, under forest canopy, where solar light is not a good option, thermal sources exist in a variety of ways, for instance, it was proved that it is possible to obtain heat from tree trunk [13].
- **Mechanical movement or vibration**. Due to wind in a field or forest, or due to underwater currents in rivers or due to any natural movement, mechanical vibration of Things is an option where piezoelectricity can be used. For example, a small waterfall can be used to obtain rotational movement to rotate a dynamo. Another example, the tree leaf movement due to wind can be harnessing.

#### *4.1.1. An example of IoNaT thing: a smart tree*

As described in [13], it is possible to get temperature gradients[2] at different tree trunk depths and to take advantage of the natural temperature control of the trees, that maintains that gradient, and convert it into electric energy.

It was proved that, as a tree trunk is a living organism, the temperature gradient $\Delta T$ between any annual ring and the external temperature can be slightly constant or presents slow increment or decrement as the external temperature varies, as shown in **Figure 3**. The explanation to this is that trees try to remain in a comfort zone despite its external temperature regulating their temperature.

**Figure 4** shows the experimental results when the temperature was measured in three different depths of a tree[3]: 100 mm, 75 mm and 50 mm and the external temperature. As can be noted, the deeper the depth, the bigger is the $\Delta T$. This result indicates that the depth to install the energy harvesting transducer can be chosen accordingly to the voltage level that is required. An interesting point that worth to be highlight is that either at daylight or during the night, $\Delta T$ exists with an inversion at 18:00 (6 pm) and at 6:00 (6 am), the local twilight hours, showing to be possible to harvest thermal energy all day long.

A possible implementation of the tree trunk energy harvesting transducer is shown in **Figure 5**.

### 4.2. WSN as a solution for communication in the IoNaT concept

Wireless sensor networks (WSNs) are an important technology for large-scale monitoring, providing sensor measurements at high temporal and spatial resolution [31–33]. In general, WSNs are composed of a large number of low-cost and low-power sensor nodes communicating at distance and sink nodes. Routing nodes and cluster head nodes are also used in WSNs.

[2]Temperature gradients are the temperature difference between the two bodies over a specified distance between them.
[3]The tree is of the species *Adenanthera pavonina*, commonly called red lucky seed, located in the City of João Pessoa, PB in Brazil.

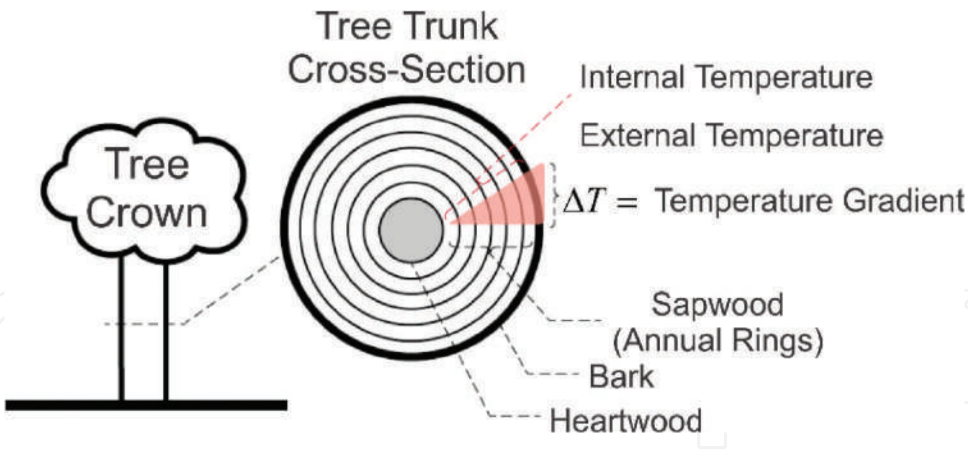


**Figure 3.** Temperature gradient comes from different annual rings related to external temperature [13].

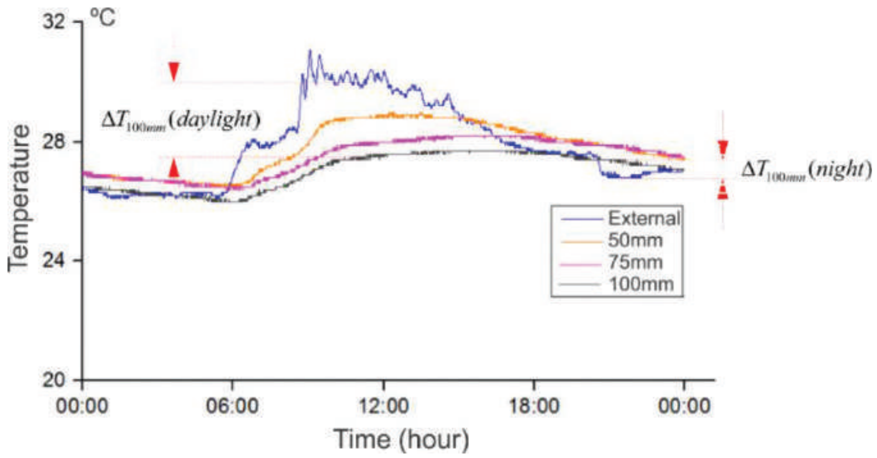


**Figure 4.** Temperature measurement in three depths of a tree: 100, 75 and 50 mm and the external temperature.

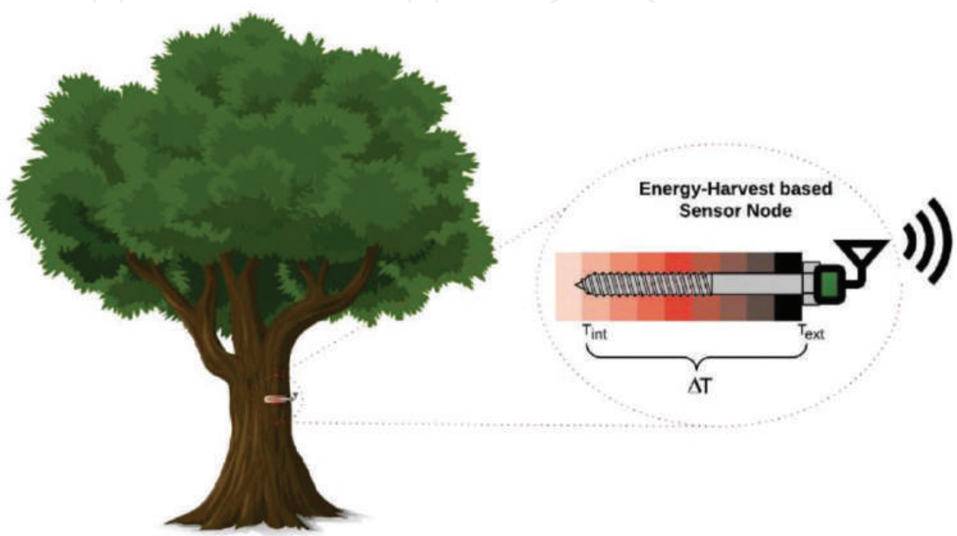


**Figure 5.** A possible implementation of the tree trunk energy harvesting transducer.

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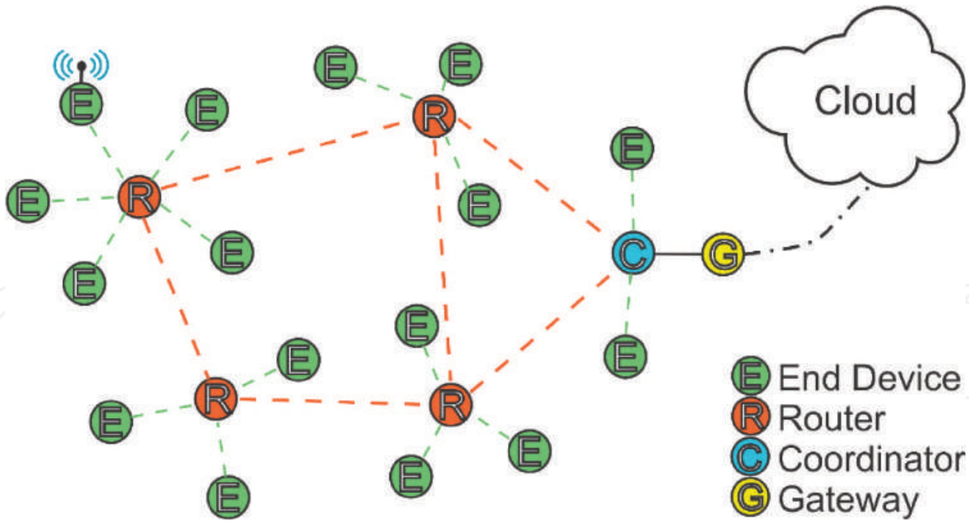


**Figure 6.** Typical wireless sensor networks.

WSN technology was triggered by the availability of low-cost low-power feature-rich microcontrollers and single-chip radio transceivers [31].

**Figure 6** shows a general structure of a WSN in a very popular implementation, which comprises of the following three nodes [34, 35]:

- **End device** (also called sensor node): It contains functionality of sensing and communicating with its parent node (the coordinator or a router) and does not participate in routing.
- **Router**: It acts as an intermediate device, and its main function is to participate in multihop/mesh routing of network messages permitting them to propagate over long distances.
- **Coordinator** (also called sink node): It controls the entire WSN, initiates the network and is capable of bridging other networks, generally, using a **gateway**. In general, currently, the gateway is used to connect the WSN to some Cloud service as data storage, analytics, visualization, and so on.

An important application of WSN technology is in environment monitoring [called environmental sensor network (ESN)] that has attracted considerable research interests in recent years [36], and they can be applied in pollution monitoring, meteorological conditions measurement (e.g., temperature, wind velocity, solar radiation, atmospheric precipitation etc.), forest fire, seismic activity, etc. [37]. In addition, depending on the density of nodes distributed in a natural environment, WSN technology presents potential to support communications in the presence of vegetation due to the short distances involved.

The environmental sensor network is directly related with IoNaT paradigm because currently, it is possible to utilize low-power System-on-Chip (SoC[4]), which integrates microcontroller, some peripherals and RF radio, to design nodes for the network capable of running with extreme low energy [38]. In addition, modern SoCs with RF communication

[4]An SoC is an integrated circuit that integrates some components in the same chip like processor, digital, analog, mixed-signal peripherals and RF transceiver—all on a single chip.

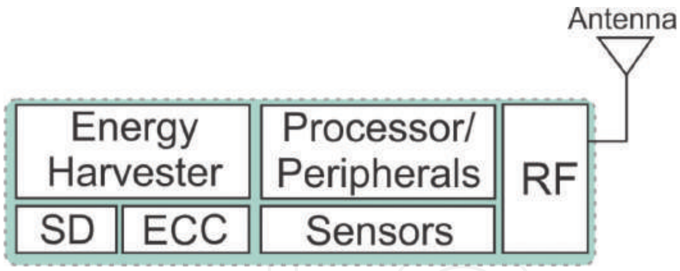


**Figure 7.** IoNaT node. SD: Energy storage device. ECC: Energy conditioning circuit. RF: RF transceiver.

capability have different low-power or sleep modes to save energy during times of inactivity. The management of these modes is very important in relation with an energy harvesting strategy allowing to refill the energy storage device during these periods of low activity [16].

Considering the environmental sensor network, energy harvesting and low-power RF SoC, a possible structure for an IoNaT node is shown in **Figure 7**.

It is important to observe that as the data coming from IoNaT nodes would be sporadic and with an extremely low data rate, potential technologies to implement an IoNaT-node network may be those based on the IEEE 802.15.4 physical radio specification [39], particularly, for example, ZigBee [40] that features low-power and low-bandwidth capabilities. Another potential technology for the same purpose would be LoRaWAN [41] that is a low-power wide-area network (LPWAN) that features low-power and low-bandwidth capabilities, but is still capable to sustain long-range wireless connections. However, LoRaWAN only implements star topology.

## 5. Conclusion

An Internet of Natural Things (IoNaT) approach has the potential to be fully developed and gain the same attention as the IoT in a near future. However, to obtain such a development and at the same time, to be an environment-friendly option, it is mandatory to avoid using chemical batteries and to use technologies based on energy harvesting along with wireless sensor networks. In the context of IoNaT, it will be possible to take advantages of modern technology and, as a consequence, to incorporate services as environmental monitoring for impact assessments of human activities, animal surveillance, plantation monitoring and other services related to natural environments.

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## Conflict of interest

There is no conflict of interest to report.

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Chapter 3

# CCHP System Performance Based on Economic Analysis, Energy Conservation, and Emission Analysis

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Hossain Azam

Additional information is available at the end of the chapter

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**Abstract**

This chapter includes the basic configuration of combined cooling heat and power (CCHP) systems and provides performance analysis based on energy, economic and environmental consideration applicable to buildings. The performance parameter for energy savings measure used for the analysis is primary energy consumption (PEC) of CCHP system. Parameters used for economic analysis are the simple payback period (SPP), annual savings (AS), internal rate of return (IRR) and equivalent uniform annual savings (EUAS). The emissions savings are determined for carbon dioxide (CDE), nitrogen oxides ($NO_X$), and methane ($CH_4$). Economic, energy, and emission performance criteria have been utilized for three types prime movers in five different building types, consisting of a primary school, a restaurant, a small hotel, an outpatient clinic, and a small office building. Performance for economic analysis indicated that economic savings career, unlike ICE, which is preferable in terms of economic and energy savings, emission analysis shows that micro-turbine poses be observed for the ICE in all building types, and the micro-turbine in some building types. For all types of prime mover based CCHP systems, lower $CO_2$ emission is observed for all building types. However, emission characteristics compared to other types of prime movers. Overall, CCHP system with optimum use of its appropriate prime movers can provide potential energy, economic and environmental benefit in buildings.

**Keywords:** CCHP systems, energy, ICE, micro-turbine, fuel cell, emission reduction, economic analysis

## 1. Introduction

Global energy demands are increasing on a daily basis and these demands are still being met with conventional methods of power generation such as burning coal and gasoline [1]. These resources are not only limited but also are detrimental to our environment [2]. Among different power consumers, buildings are major energy sink comprising 40% of total U.S. energy consumption [3]. Thus, the increasing demand for sustainable buildings with the constant need of cooling and heating power in buildings calls for improving traditional energy production and optimum use. One method to produce sustainable energy is to adopt the combined cooling, heating, and power (CCHP) technology, which is also known as trigeneration. Today, the CCHP system has proven effective in ensuring energy savings, as well as reducing the emission of pollutants [4]. This technology is a more advanced form of the combined heating and power (CHP) system and is becoming widely accepted with consumers. While a CHP system involves the simultaneous production of two types of energy such as electricity and heat, usually in the form of either hot water or steam, from one primary fuel, such as natural gas; the CCHP system, as the name implies, produces three forms of energy: electricity, heat, and chilled water [5]. Chilled water is achieved by incorporating an absorption chiller into a cogeneration system. Absorption chillers use the waste heat from a CCHP system to create chilled water to cool buildings. Introducing an absorption chiller into a CHP system allows a site (e.g., buildings) to increase its operational hours through the increased use of heat, which ultimately reduces energy costs [6]. Because of its abilities to save energy, reduce emissions, and provide economic benefits, the CCHP system has attracted much attention worldwide.

Burning fuels such as natural gas or coal results in significant amounts of heat energy and waste materials. Generally, a mechanical apparatus converts the heat energy into electrical energy [7]. However, a significant portion of heat energy is wasted and discharged into the environment [8], and such unused heat energy has significant potential that a CCHP system exploits. First, CCHP accomplishes cooling that is used to provide air conditioning, as the heat produced during electricity generation can be used to drive absorption chillers. Second, the CCHP makes maximum use of the waste heat from the prime movers to supply heat to the buildings and provide hot water for industrial processes. In this way, a CCHP system maximizes heat energy use in buildings and increases the prime mover efficiency. In the literature, it was reported that CCHP systems could yield efficiencies more than twice that of average power plant efficiency [9–11]. On the contrary, this percentage is not always constant. The electrical load may remain almost constant throughout the year and thus can maintain a certain level of fuel consumption. However, the demand for cooling and heating varies throughout the year. The demand for cooling is higher during summer and that for heating is higher during winter. However, during spring and fall, the need for both cooling and heating may decrease significantly, and in such cases, the efficiency of the CCHP system may decrease. However, this technology allows greater operational flexibility at sites (e.g., buildings) that demand energy in the form of heating as well as cooling [12]. That specific benefit is attractive in tropical countries where buildings need to be air-conditioned in all seasons as well as to industries that require process heating and cooling over the year. Finally, a CCHP system generates power in a way similar to that of conventional systems and can be utilized as a backup power system. This also reduces fuel and energy costs and $CO_2$ production compared to electricity produced from coal. All of these advantages have made the CCHP systems an economically viable alternative to produce power as well as to condition the building environment [13]. This chapter describes the history of CCHP, provides basic CCHP configuration, specifies types of prime movers, and provides performance parameters with basic economic analysis applicable to buildings. The results shown here include the use of CCHP in a cold, climate (Minneapolis, MN) for five different building types, consisting of a primary school, a restaurant, a small hotel, an outpatient clinic, and a small office building. The evaluation criteria to measure the performance parameters of the CCHP system are economic benefits, energy conservation, and emissions mitigation. Parameters indicating cost savings are the simple payback period (SPP), annual savings (AS), internal rate of return (IRR), and equivalent uniform annual savings (EUAS). The energy saving parameter used is primary energy consumption (PEC). The emission savings are determined for carbon dioxide (CDE), nitrogen oxides ($NO_X$), and methane ($CH_4$). Overall, the CCHP system has significant energy saving potential in both buildings and industries. It can also provide maximum sustainability in energy utilization in modern buildings.

## 2. History

Since the beginning of the electric age, power plants produced far more heat than electricity. In 1882, Thomas Edison used cogeneration of both steam and electricity in the world's first commercial power plant in New York [14]. Then, at the beginning of the twentieth century, steam became the principal source of mechanical power [15]. At the same time, energy became more controllable and many small power houses that produced steam to customers for space heating or industrial use realized that they might also produce electricity as well [16]. Because steam cannot be transported far without a significant loss of heat, cogeneration was dependent on a district energy strategy for small community plants. After World War II, there was significant growth in centralized power plants that could deliver electricity over a wide region [17]. During 1940–1970, the concept of a centralized electric utility that could deliver power to the surrounding area was developed, and as a result, steam no longer was a viable commodity. During that time, large utility companies became both reliable and comparatively inexpensive sources of electricity. That situation caused small power houses to stop using the CHP system and instead, they bought their electricity from the large utility companies. Further, as central utilities became more reliable and less costly, CHP remained economical only in industries that required large amounts of steam.

During the late 1960s and early 1970s, interest in CHP began to revive, and by the late 1970s, the need to conserve energy resources became clear [18]. During this time, legislation was passed in the United States to promote cogeneration because of its efficiency. Specifically, the Public Utilities Regulatory Policies Act (PURPA) of 1978 encouraged this technology by allowing CHP producers to connect to the utility network and to purchase as well as sell electricity. In times of shortfall, PURPA allowed CHP producers to buy electricity from utility companies at fair prices and also allowed them to sell their electricity based on the cost the utility would have paid to produce that power [19]. These conditions encouraged a rapid increase in CHP capacity in the United States. However, at that time, there was little government support for CHP in Europe because the cogeneration was not seen as a new technology and therefore was not covered under the European Community's energy program. However, some individual European countries, like Denmark and Italy, adopted separate energy policies that allowed them to incorporate CHP facilities in their future energy projects. At present, the EU generates 11% of its electricity using cogeneration [20]. Because of the price increment of energy types on the market and the need for heating and cooling energy in modern buildings, considerable research has been conducted to improve the CHP system [21]. The historical basis and success of CHP then led to further steps to expand the efficiencies of CHP to CCHP, as each new increase in energy recovered will result in higher efficiencies, lower fuel/energy costs, and fewer related emissions.

## 3. Basic CCHP system design configuration

Combined cooling, heating, and power (CCHP) systems consist of a decentralized power generation source where a portion of the heat released as a byproduct of generation eventually gets recovered rather than rejected to the atmosphere. There are four main units of a CCHP system: (a) power generation unit, which is referred to as the plant's prime mover, such as a gas turbine, (b) cooling unit, such as a single-effect absorption chiller, (c) a heating unit, such as the boiler, and (d) electrical generator as shown in **Figure 1**.

In the typical CCHP system, mechanical power is produced from a thermal generation unit, such as a gas turbine. The mechanical power produced gets utilized to rotate an electrical generator. The generation unit produces waste heat, including exhaust gases and lubrication oil that is recovered to meet the cooling and heating demands of the building or industrial unit. One portion of waste heat is used to meet the heating demand, such as a building's heating load, while the remaining portion is used to meet the cooling demand. Moreover, cooled water from the chiller is used as a working fluid for the heat supply from the condenser and absorber of the chilling machine. CCHP systems provide cooling by using low quality heat (low temperature

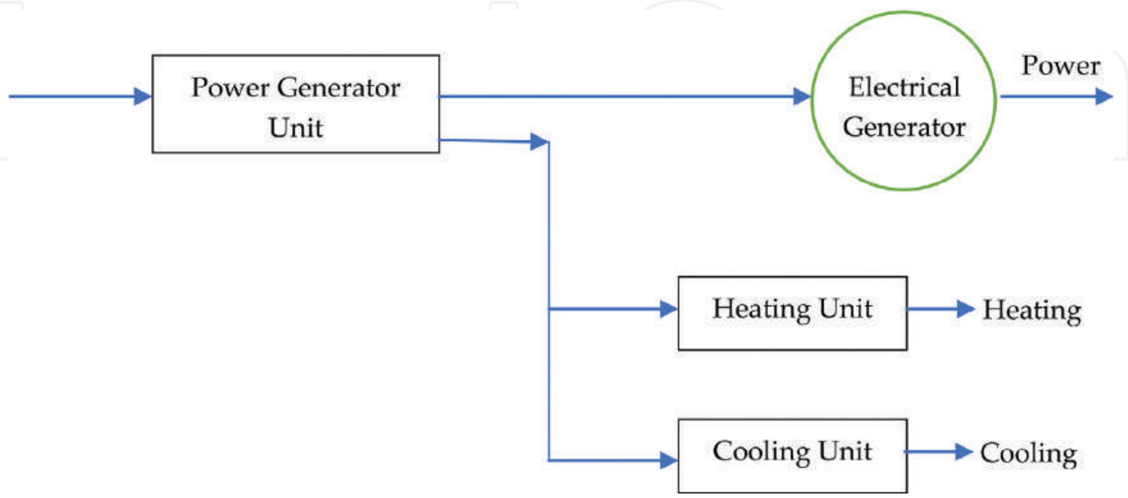


**Figure 1.** Schematic of a typical CCHP system.

and low pressure) discharged from the prime mover to drive the adsorption chillers and thus reduce the primary energy consumption overall.

## 4. Prime movers

The adoption of the CCHP system in buildings is mainly dictated by the main component of the CCHP system, its prime mover. Other components of the CCHP system (e.g., heating unit and cooling unit) do not have significant effects on its adoption in buildings. Several types of prime movers have been utilized for CCHP systems, including internal and external combustion engines, steam, gas, and microturbines, and fuel cells [22]. These different types of prime mover distinguish one CCHP from another. The number of prime movers varies depending on the electricity load demand. Operating with more than one fuel type adds flexibility to the prime mover's operation. However, the fuel type affects the greenhouse gas emission rate. For example, natural gas combustion produces fewer greenhouse gas emissions than do diesel combustion.

An internal combustion engine (ICE) system (**Figure 2a**) is the most common type of a prime mover. The merit of ICE systems depends on how often CCHP generation is required [23]. In this system, heat can be recovered from exhaust gases and the engine's cooling circuit. Moreover, heat is generated from exhaust gases for the absorption chilling machine. Cold water limits the operating temperature of the engine and uses thermal energy from exhaust gases in

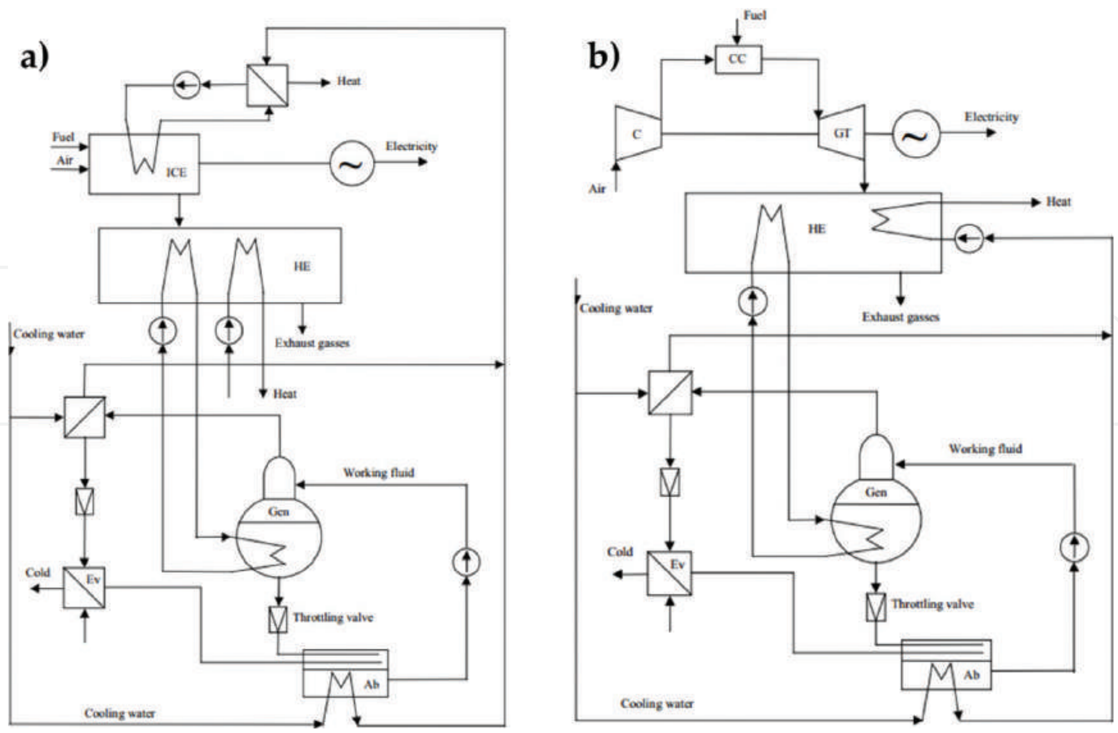


**Figure 2.** Simplified scheme of a trigeneration plant with (a) internal combustion engine with absorption chilling machine and (b) gas turbine with absorption chilling machine [23].

the heat exchanger to generate hot water or steam. In most cases, it is used to produce cooling energy by electric refrigerators. On the other hand, when the prime mover is a gas turbine (**Figure 2b**), the turbine generates electricity. In this case, heat generated from exhaust gases can be delivered to the users and a portion of it is used as a driving force for the absorption chilling machine. The other mechanisms are similar to those in the ICE system.

The prime mover of a steam turbine CCHP system is a steam boiler that needs fuel and air input to produce high pressure steam that feeds the steam turbine. When steam expands in the steam turbine, a portion of the thermal steam energy is transformed into mechanical energy. Moreover, the rotor of the electric generator is connected to the same turbine shaft, so ultimately, the mechanical energy is transformed into electricity.

The CCHP system design with microturbines is slightly older and dates back to the twentieth century [21]. Microturbines are small electricity generators that burn gaseous and liquid fuels to create high-speed rotation that turns an electrical generator. These are ideal prime movers for decentralized CCHP systems with small-scale rated power (**Figure 3**). This system has attracted attention because it has several benefits over other prime movers. The size range for microturbine available and in development is from 30 to 400 kilowatts (kW), while conventional gas turbine sizes range from 500 kW to 350 megawatts (MW) [24]. Moreover, microturbines run at high speeds and, like larger gas turbines, are able to operate on a variety of fuels, including natural gas, sour gases (high sulfur and low Btu content), and liquid fuels, such as gasoline, kerosene, and diesel fuel/distillate heating oil [25]. In resource recovery applications, they burn waste gases that otherwise would be flared or released directly into the atmosphere.

The CCHP system that uses the Stirling engine (**Figure 4**) as a prime mover can be used as energy sources for small commercial and residential buildings. It can operate with a wide variety of fuels, including all fossil fuels, biomass, solar, geothermal, and nuclear energy [26]. The external combustion that controls the combustion process results in low emissions, noise, and waste heat flow [27]. Another major advantage of the Stirling engine is that it can work at low temperatures [28].

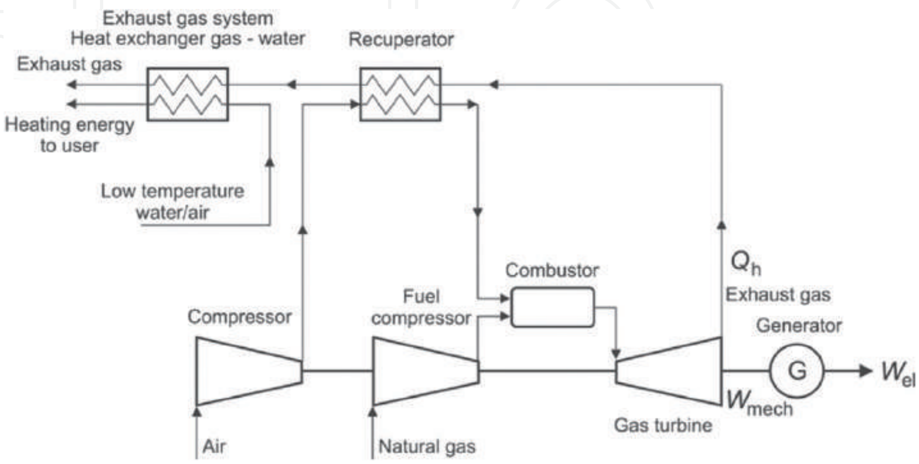


**Figure 3.** CCHP system design with a microturbine as a basic aggregate [21].

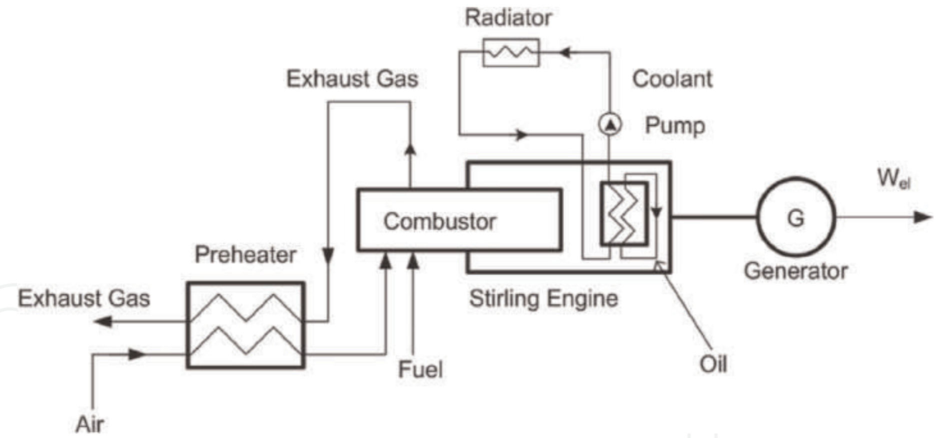


**Figure 4.** CCHP system design with the Stirling engine as a basic aggregate [21].

CCHP systems with a fuel cell as a prime mover are promising because of their potential to generate electricity and thermal energy directly. In this system, membrane steam reformers purify hydrogen without cooling the reactor's effluent. Before electrooxidation at the fuel cell's anode, only permeated hydrogen needs to be cooled. Both the absorption and compression heat pumps use the fuel cell's waste heat and electricity for heating and cooling applications [29]. Moreover, high-temperature fuel cells combined with an absorption chiller offer the potential to meet the criterion of virtually zero pollutant emissions [30].

## 5. Performance parameters of CCHP

In order to determine the best performance parameters and boost the performance for the CCHP system, several equations have been applied. Equations to determine the GHG emissions [e.g., carbon dioxide (*CDE*), nitrogen oxides (*NXE*), and methane (*ME*)] have been set as well. Moreover, methods to calculate the annual cost savings and primary energy consumption (*PEC*) can also be represented with appropriate equations and are presented in [31]. All of these equations to calculate the performance parameters are presented in this section. The annual cost savings have been reported as dollar amount and the *CDE*, *NXE*, *ME,* and *PEC* were reported in terms of "relative savings" with respect to the reference quantities.

### 5.1. Economic analysis

Eq. (1) can be used to calculate the total annual operating cost (*AOC*) of the CCHP system together with the reference system. Parameters $C_{NG}$ and $C_{elec}$ used in Eqs. (1) and (2) are the cost of natural gas and electricity, respectively. The operational (excluding fuel) and maintenance cost per unit of energy produced by the *PM* is designated as *COM*. The value represents the energy produced during the *i*th interval. The annual savings can be calculated by deducting $AOC_{PM}$ from the $AOC_{ref}$ as shown in Eq. (3).

$$AOC_{PM} = \sum_{i=1}^{8760} F_{mi} C_{NG} + E_{grid_i} C_{elec} + P_{PM_i} C_{om} \tag{1}$$

$$AOC_{ref} = \sum_{i=1}^{8760} F_{mref_i} C_{NG} + E_{grid_{ref_i}} C_{elec} \tag{2}$$

$$AS = AOC_{ref} - AOC_{PM} \tag{3}$$

As shown in Eq. (4), the calculation of the simple payback period (*SPP*) depends on the *AS* calculation [32].

$$SPP = \frac{IC}{AS} \tag{4}$$

where, *IC* is the initial cost. A discounted cash flow method, such as internal rate of return (*IRR*), is also used to evaluate these CCHP systems. CCHP is attractive for building operations when *IRR* is greater than the minimum attractive rate of return (*MARR*). *IRR* can be calculated from the Eq. (5).

$$IC = \mathrm{AS}\left[\frac{(1+IRR)^{L_{PM}} - 1}{IRR(1+IRR)^{L_{PM}}}\right] \tag{5}$$

where, *LPM* is the lifetime of the *PM* [29]. Another discounted cash flow method is the net present value (*NPV*) for CCHP systems. *NPV* can be calculated as shown in Eq. (6):

$$NPV = \sum_{n=0}^{N} \frac{AS}{(1+i)^n} - IC \tag{6}$$

where, *i* is the discount rate, *n* is the time of cash flow (period), and *N* is the total number of periods. A third analysis that uses discounted cash flow is the equivalent uniform annual savings. First, the equivalent uniform annual cost is determined according to

$$EUAC = IC \frac{\xi(1+\xi)^{L_{PM}}}{(1+\xi)^{L_{PM}} - 1} \tag{7}$$

where, $\xi$ is the interest rate, chosen as a representative value for bank offered rates. Equivalent uniform annual saving can then be calculated from

$$EUAS = EUAC - AS \tag{8}$$

### 5.2. Energy consumption

Savings in primary energy consumption can be calculated by

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$$PEC_s = \sum_{i=1}^{8760} \frac{\left(F_{mref_i} PF_{NG} + E_{grid_{ref_i}} PF_{elec}\right) - \left(F_{mi} PF_{NG} + E_{grid_i} PF_{elec}\right)}{F_{mref_i} PF_{NG} + E_{grid_{ref_i}} PF_{elec}} \tag{9}$$

where $PF_{elec}$ and $PF_{NG}$ are the primary energy conversion factors for electricity and natural gas, respectively. Values for this study are given in **Table 1**.

### 5.3. Emission characteristics

The equations for the reduction in emissions for all three gases considered in this study, relative to the reference system, are represented by [33]:

$$Em_{s,g} = \sum_{i=1}^{8760} \frac{Em_{ref_i} - Em_{CCHP_i}}{Em_{ref_i}} \tag{10}$$

Here, $g$ in the subscripts represents the gas for which the savings are being calculated, i.e., represents the emission savings for carbon dioxide ($g$ = $CD$), nitrogen oxides ($g$ = $NX$), and methane ($g$ = $M$) are the emissions from the reference case and are the emissions obtained when the CCHP system is operated and can be calculated by

$$Em_{CCHP} = F_m EF_{NG,g} + E_{grid} EF_{elec,g} \tag{11}$$

$$Em_{ref} = F_{mref} EF_{NG,g} + E_{grid_{ref}} EF_{elec,g} \tag{12}$$

where, $EF_{NG,g}$ and $EF_{elec,g}$ are the emission factors for the respective gases from natural gas and electric sources as shown in **Table 1**. Emission conversion factors tabulated in **Table 1** can be used to determine the overall emissions of $CO_2$, NOx, and $CH_4$. The installation location of the PM in the CCHP system and fuel types required for electricity influence the emission

| Variable | Symbol | Value | Unit |
|---|---|---|---|
| Electric cost | $C_{elec}$ | 0.0757 | $/kWh |
| Natural gas cost | $C_{NG}$ | 0.0125 | $/kWh |
| Electric $CO_2$ emission | $EF_{elec,CD}$ | 0.682 | kg/kWh |
| Natural gas $CO_2$ emission | $EF_{NG,CD}$ | 0.181 | kg/kWh |
| Electric $NO_x$ emission | $EF_{elec,NX}$ | $1.12 \times 10^{-5}$ | kg/kWh |
| Natural gas $NO_x$ emission | $EF_{NG,NX}$ | $8.54 \times 10^{-7}$ | kg/kWh |
| Electric $CH_4$ emission | $EF_{elec,M}$ | $8.26 \times 10^{-6}$ | kg/kWh |
| Natural gas $CH_4$ emission | $EF_{NG,M}$ | $1.17 \times 10^{-8}$ | kg/kWh |
| Electric PEC factor | $PF_{elec}$ | 3.5 | — |
| Natural gas PEC factor | $PF_{NG}$ | 1.09 | — |

**Table 1.** Cost of fuel and electricity, gas emissions as well as PEC factors for Minneapolis, MN [32].

conversion factors. Emission is also observed in the reference system because of the grid electricity generation produced originally in the power plant. Emissions of the reference system are also due to the local boiler. Three factors dominate the emissions caused by CCHP: (i) electricity produced by the CCHP systems, (ii) electricity generation process of the power plant, and (iii) heat produced by the boiler.

## 6. Economic analysis

The CCHP system has drawn great interest because of its potential in prolonged economic benefit with short payback on initial capital investment. However, economic benefit is not a straightforward evaluation, which depends on the equipment cost, equipment efficiency, electricity and fuel cost, building electric demand, heating and cooling load, etc. These factors depends on the local climate condition, equipment variability, budget restriction, energy saving credits, and capital incentives to use any particular type of prime mover (PM) systems. Among those, the most significant ones that affects the economics of CCHP systems are the types of PM and weather zone effect on building load. Selecting a new PM for CCHP over a reference system is not always by simple payback period analysis, the building owners or investor may inclined toward a particular PM due to any favorable capital incentives offered

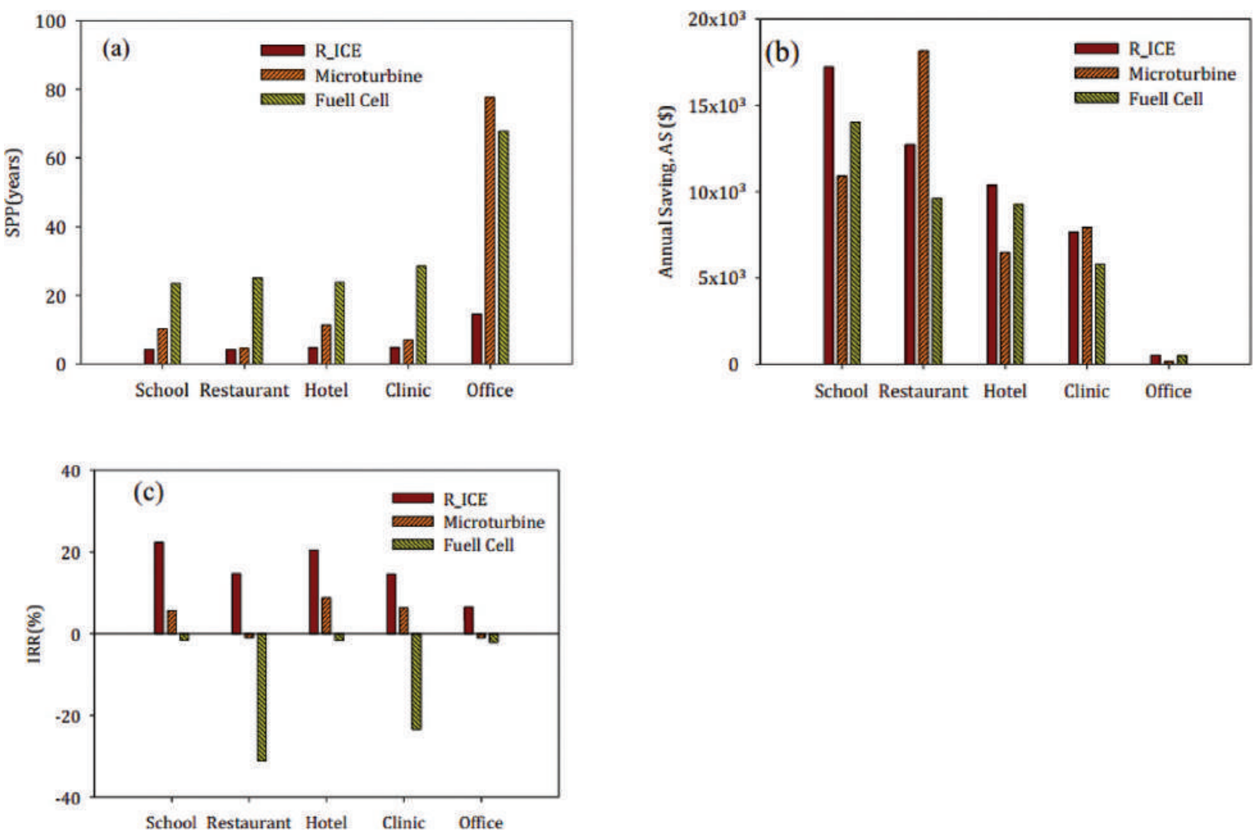


**Figure 5.** (a) *SPP*, (b) *AS*, and (c) *IRR* comparison of CCHP installed building types with the reference building [32].

by government entities. The economic benefits of the CCHP system can also be significantly affected by local climate conditions since it changes the building heating and cooling demand.

Generally, the parameters used to determine economic benefits are the simple payback period (*SPP*), annual savings (*AS*), internal rate of return (*IRR*), and equivalent uniform annual savings (*EUAS*). Previous research has shown that the CCHP system is able to satisfy the energy demands of a building when it is integrated with the electric grid to achieve positive values of EUAS, IRR, and *AS* [32]. **Figure 5** shows the economic benefits for the three different prime movers in a case study conducted in Minneapolis, MN. The reciprocating internal combustion engine (*ICE*) demonstrated the greatest economic benefits overall across all building types. It also resulted in the best *IRR* values among the three prime movers. Moreover, the reciprocating *ICE* provided the maximum savings based on the *EUAS* values calculated. Based on the study, a fuel cell was the least economically advantageous and resulted in negative *EUAS* values for all building types. The reason for the net loss is attributable to the high capital cost of the fuel cell. However, the selection of a new prime mover for the CCHP generally depends on the analysis of economic parameters, as well as project details. Further, budget restrictions, credits for energy saving, and capital incentives need to be considered when selecting the prime mover.

## 7. Energy conservation

The CCHP system is an effective way to save energy over customary system with separate cooling and heating systems as it uses prime mover exhaust to heat and cool the building. This provides an alternative for the world to meet and solve energy-related problems, such as energy shortages and supply security, emission control, etc. Comprehensive analysis is often warranted to decide on appropriate prime mover for a CCHP system, which relies on the tradeoffs between energy savings, environmental impacts, and economics benefit. CCHP system's energy performance is greatly depends on the site weather zone, it works with maximum efficiency where heating, cooling, and electricity demands are mostly uniform through most or all of the year. However, energy savings will be significantly high if the installation site has higher heating demand, as it is more efficient to utilize the low quality thermal energy from PM exhaust to heat the facility rather use that energy to cool the building.

Generally, the energy conservation parameter for the study is the primary energy consumption (*PEC*) [32]. Another parameter, referred to as site energy consumption (*SEC*) always increases when the CCHP is used [33]. In contrast, the PEC is a better indicator of energy feasibility because of its potential to decrease when the CCHP is operational [33]. **Figure 6** shows the PEC results of the energy analysis in the case study conducted in Minneapolis, MN, where the reciprocating ICE and fuel cell showed almost similar energy (PEC) savings. All types of buildings experienced reductions in PECs when a CCHP system was adopted. When only the primary energy savings are considered in the absence of an economic analysis, all three prime movers are good options for the three building types.

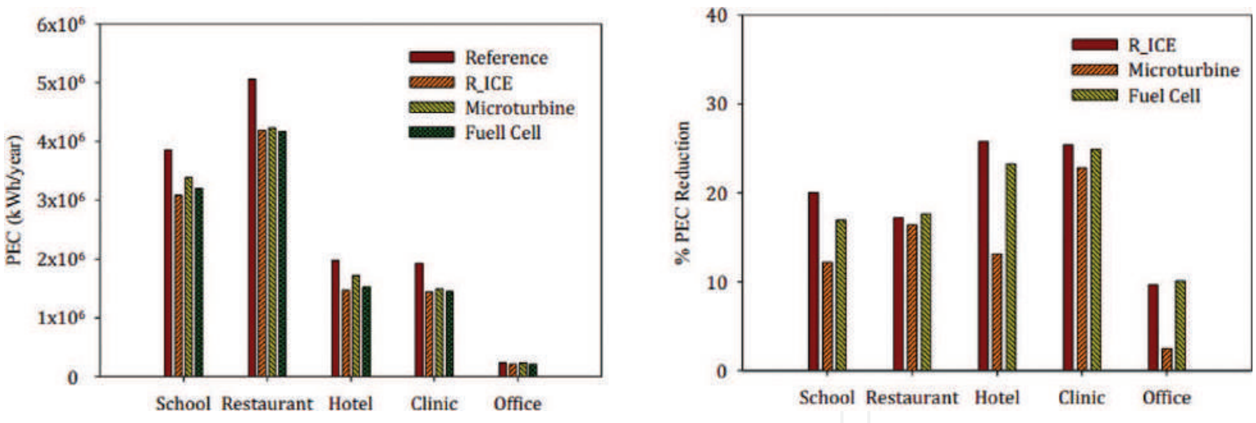


**Figure 6.** PEC comparison of CCHP installed building types with the reference building in Minneapolis, MN [32].

## 8. Emission analysis

Emission savings could be a significant decisive factor to implement the CCHP system over traditional heating and cooling system separately. Government agencies or ecofriendly industries are always inclined toward installing energy systems (i.e., CCHP) with better emission characteristics even with non-attractive economic benefit. In recent years, various federal, state or local government agencies offered carbon credit as an emission incentive to promote energy efficient technology like CCHP systems to industries and residential consumers. The CCHP system could be economically feasible with carbon credit even when SPP, IRR, and EUAS show negative economic return for the CCHP system over a traditional building air conditioning unit.

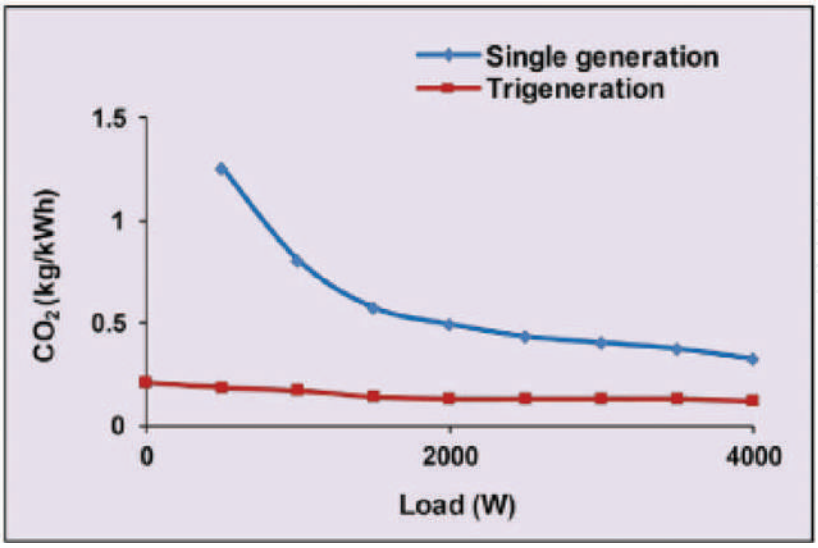


**Figure 7.** Sample of variation of carbon dioxide with load [34].

CCHP reduces $CO_2$ emissions significantly across a varying range of loads typical of micro-scale systems. **Figure 7** shows that $CO_2$ emissions per unit (kWh) of useful energy output results in a 61% reduction of $CO_2$ when a trigeneration system operates at full load compared to a single generation system [34].

A case study conducted a detailed emission analysis for a CCHP system to compare it to emissions of a reference system, which is presented in [30]. **Figures 8–10** summarize

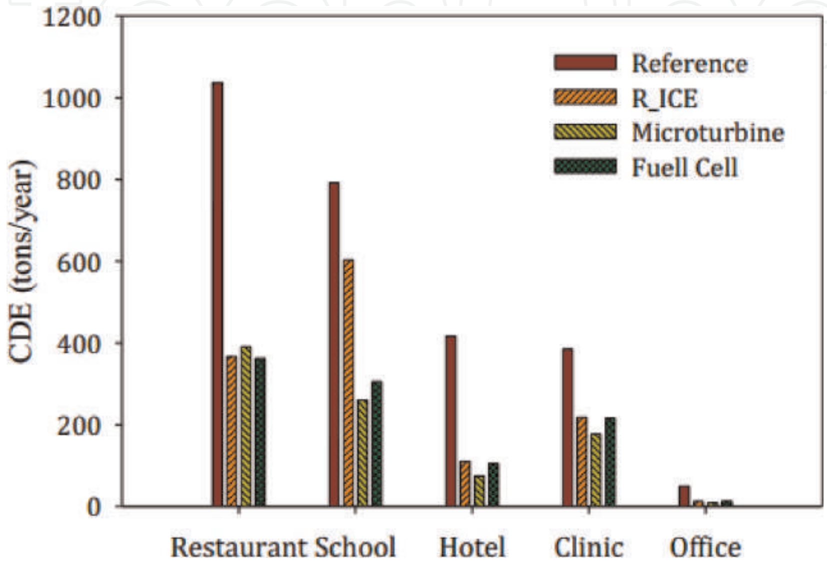


**Figure 8.** $CO_2$ emissions of reference building compared with CCHP installed different building types in Minneapolis, MN [32].

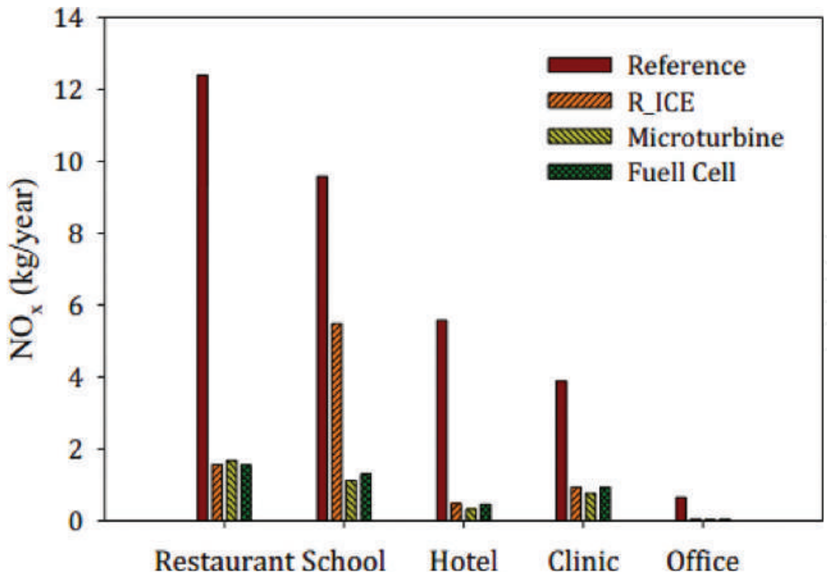


**Figure 9.** NOx emissions of reference building compared with CCHP installed different building types in Minneapolis, MN [32].

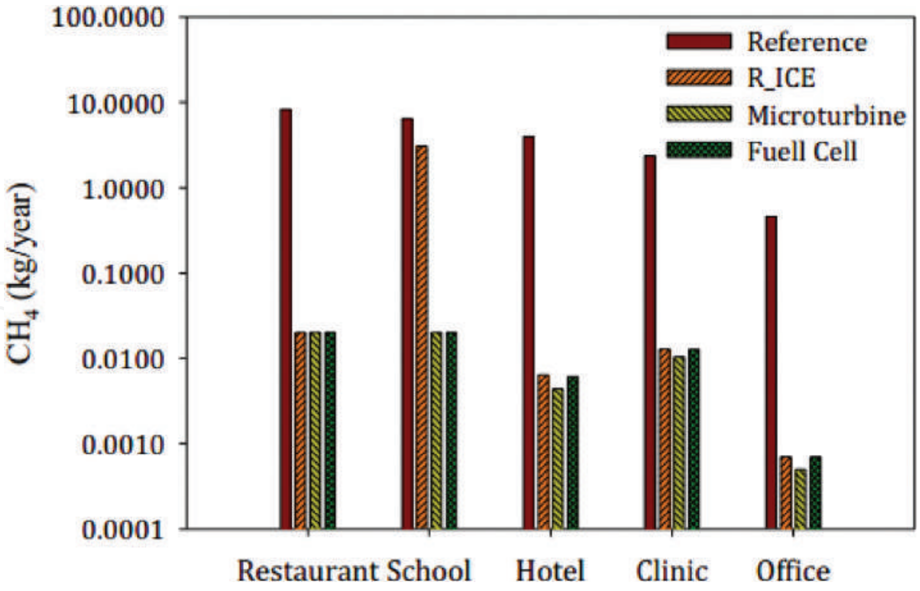


**Figure 10.** $CH_4$ emission of reference office building compared with CCHP installed building in Minneapolis, MN [32].

those emission results for the three gases analyzed. All three prime movers reduced emissions significantly and the microturbine provided the greatest reduction. For different building types, carbon dioxide emission savings show the highest savings occurred for the small hotel and small office. The reduction in carbon dioxide in the small hotel from the reciprocating ICE, microturbine, and fuel cell were 73.7, 82.0, and 74.9%, respectively. Overall, all building types experienced a reduction in emission from the implementation of CCHP systems. All three prime movers provided significant reduction in emissions; however the microturbine provided the most.

## 9. Summary

Buildings are major energy sink comprising 40% of total U.S. energy consumption. Energy savings in buildings often do not come with economic and/or environmental benefit. Additionally, the optimum use of energy and prevention of energy loss in buildings can entail additional challenges. This chapter on CCHP shows significant promise of CCHP being adopted in buildings widely not only because of its superior capacity for optimum energy use/savings but also for its additional economic and environmental benefit. It is evident that the evolution of the CHP system to CCHP system makes it more beneficial for its wide scale use in buildings. Appropriate performance parameters relevant for buildings' energy, economic and environmental benefit were determined and applied to assess the different prime movers use in CCHP for buildings. A CCHP system either with ICE or microturbine prime mover shows significant benefit in terms of energy, economic and environmental consideration for buildings. Thus, CCHP has significant role to play for overall energy independence of buildings in twenty-first century.

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# New Passive Cooling as a Technique for Hot Arid Climate

Amr Sayed Hassan Abdallah

Additional information is available at the end of the chapter

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**Abstract**

Cooling of buildings is an essential target for engineers and builders in the hot arid climate of Egypt. New cooling system was integrated into a single room built in Assiut University (El-Gorib site) in Assiut, Egypt. A passive cooling technique was integrated inside a short wind tower made from expanded paper (wet pad) 0.1 m thick. A water tube was installed on the top of the expanded paper with small nozzles. The results show that outlet air temperature from the wind tower is 27.3°C. The calculated predicted mean vote (PMV) is within the recommended range (−0.5 < PMV < +0.5). This indicates that occupants remain satisfied with indoor thermal environment after using the passive cooling system and the difference is nearly 6–7 K between outdoor and indoor. The system achieves the acceptable airflow rate with an average of 450 ppm for $CO_2$ concentration during daytime. The relative humidity did not exceed 57% most of the time. The maximum airspeed inside the solar chimney was 3.5 m/s under the effect of a high solar radiation of 890 W/m². The findings show that solar chimney with passive cooling tower design (SCPC) system achieves comfortable thermal conditions with a significant improvement in building energy conservation.

**Keywords:** inclined solar chimney, passive cooling, thermal comfort, carbon dioxide concentration

## 1. Introduction

Solar chimney with passive cooling tower design (SCPC) is a system that uses solar energy that strikes the aluminum and glass in a chimney to generate a buoyancy force in the chimney. This force drives outside hot air to pass through the evaporative pad (expanded paper) and causes reduction of indoor temperature, high humidity and constant enthalpy [1]. The thermal performance of solar chimneys using different configurations has been experimentally investigated by different researchers. The concept of metallic solar wall (MSW) on a full-scale model was studied for a single-room house under tropical climatic conditions in Thailand. It was shown that a MSW with 2 m height and 0.145 m air gap (cavity between glass and aluminum) can produce a mass flow rate up to 0.02 kg/s for a house with a base area of 11.55 $m^2$ and a height of 2.68 m and optimum natural ventilation. Such low-cost solar chimney construction can significantly reduce heat gain in the house by creating adequate flow rate to improve thermal comfort [2]. The thermal performance of a solar chimney was investigated on a full-scale model under Mediterranean daylight and night-time conditions for natural ventilation. A 4.5 m high, 1.0 m wide and 0.15 m thick reinforced concrete wall was used as a solar absorber, whose southern surface was painted matte black with insulation on the side and back surfaces. The absorber wall was covered by glass of 0.1 m thickness to reduce the convection heat. With this configuration, a maximum flow rate of 374 $m^3$/h was reported at a solar intensity of 604 W/$m^2$ occurring at around 13:00 h. Discharge coefficient was experimentally determined to carry out volumetric flow rate calculation. It was concluded that the airflow rate through a solar chimney system is greatly affected by the pressure difference between openings caused by thermal gradients and by wind velocity [3]. An experiment of solar-induced ventilation strategy was conducted. The experiment consisted of two parts, namely, a roof solar collector and a vertical stack. The purpose of the roof solar collector was to capture as much solar radiation as possible, thus maximizing the air temperature inside the channel of the roof solar collector. The heated air inside the channel rose and flowed into the vertical stack due to the pressure difference between the two zones. Meanwhile, the vertical stack was important in providing significant height for sufficient stack pressure. The walls of vertical stack were insulated to minimize the heat loss to the environment. The findings indicated that the proposed strategy was able to enhance the stack ventilation, both in semi-clear sky and overcast sky conditions. The highest air temperature difference between the air inside the stack and the ambient air was achieved in the semi-clear sky condition, which was about 9.9°C (45.8–35.9°C). Besides, in the overcast sky condition, the highest air temperature difference was 6.2°C (39.3–33.1°C) [4]. Also, an experimental study of a vertical channel simulating a solar chimney and a Trombe wall was conducted. The vertical channel had a transparent cover and an absorber plate, painted matte black. The vertical channel was open at both ends, and its dimensions were 1.025 m high, 0.925 m wide and 0.02 m–0.11 m variable depth. Heat input to the absorber plate was supplied by electrical means (200–1000 W) in steps of 200 W. Air temperature and velocity measurements inside the channel were obtained. The results showed that air temperature was increased continuously along the channel height, while the cover and the absorber plate temperatures were not. The cover temperature, as well as the absorber plate temperature, increased continuously to the middle height and then began to decrease. The authors concluded that the mass flow rate is a function of the heat input as well as on the channel depth, while the efficiency of the system is a function of the heat input only [5].

It was concluded that a serious problem of discomfort exists inside houses in projects of new Assiut city based on natural ventilation strategy only [6–9]. Traditional passive techniques were used in ancient architectures to achieve the desired summer comfort without the need for mechanical cooling systems [10]. This traditional technique was based on natural environmental conditions such as wind, water and vegetation to achieve significant indoor thermal comfort [11]. It was concluded that if passive solar solutions are integrated in existing buildings, building energy demand can be reduced [12]. Many researches have been conducted to examine passive cooling strategies in the buildings. Maerefat and Haghighi studied solar chimney integrated with evaporative cooling cavity. This integrated system was capable of providing good indoor conditions during daytime in the living room [10]. Alemu et al. developed a model using passive cooling technique in earth air tunnel. This model investigated the integration of passive techniques [13]. Developing solar chimney with direct evaporative cooling tower using numerical simulation was done using COMIS-TRNSYS software to provide indoor thermal comfort under the climatic conditions of Assiut, Egypt. The results show that the system generates 130.5 $m^3$/h with indoor thermal comfort of 80% acceptable range [7, 8]. Macias et al. developed a passive cooling system for a residential building. Natural ventilation was enhanced with the aid of a solar chimney, and fresh air was cooled down by circulation within the duct area of the building. It was found that the passive cooling system allowed for ensuring thermal comfort through low conventional energy consumption based on a 2-year monitoring period [14] .

No experimental studies were found for the integration of solar chimney with cooling strategies in residential buildings in Egypt except for the ventilated Trombe wall as a solar heating and cooling for building retrofitting in semiarid climate (Saint Katherine, Egypt) [15]. The purpose of using solar chimney is to generate natural air movement and improve stack-induced ventilation with low $CO_2$ concentration and indoor comfort for low-energy buildings in Egypt. The main aim of this study is to investigate the performance of an (SCPC) integrated within a room as a passive cooling technique to provide sufficient fresh cooled air, indoor comfort, and reduce room cooling loads. This stage is the second phase of a project for developing an integration of solar chimneys with passive cooling technique (SCPC) to reduce energy used in buildings in Assiut, Egypt.

## 2. Test room and SCPC system description

A single room was built in Assiut University (El-Gorib site) in Assiut, Egypt. Room dimensions are 3.8 x 3.8 x 2.8 m (L × W × H) based on the previous numerical model of solar chimneys integrated with passive cooling [7, 8]. It is located at a latitude of 27°3′N and a longitude of 31°15′ E. In terms of climatic characteristics, Assiut is located in southern Upper Egypt zone. It is characterized by hot dry summers with a maximum outdoor temperature that ranges from 41–46°C and a minimum temperature that ranges from 16–21°C in the summer months. This zone has a global radiation range of 1000 to 1125 W/$m^2$ in the summer and 650 to 800 W/$m^2$ in the winter. Outdoor climate analysis was done based on field measurements at 2-minute time interval to analyze 1-year data (2015). **Figure 1** shows the temperature and humidity patterns of 2015. Selecting 2 months for monitoring (August and September) was done to test indoor environment using passive air conditions. These periods were selected to

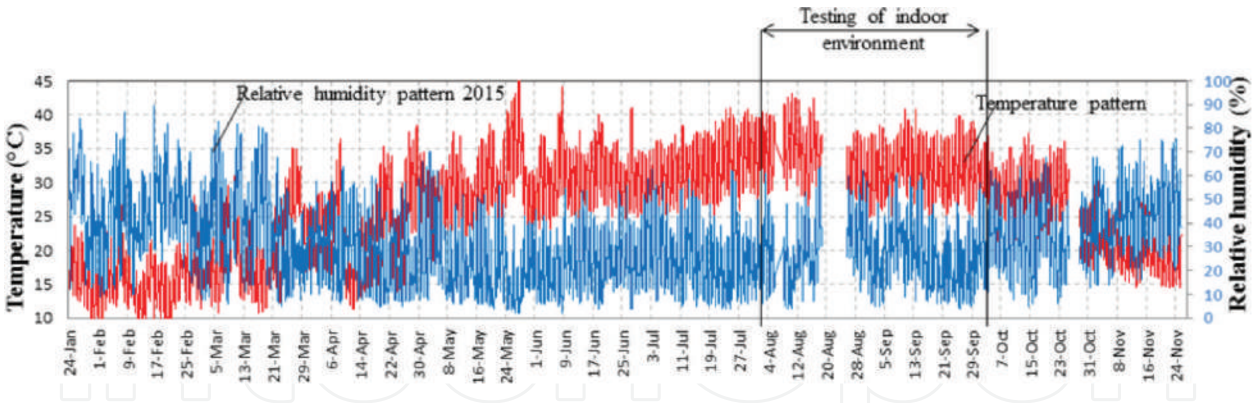


**Figure 1.** Temperature and humidity pattern of outdoor condition during the year of 2015.

investigate the effect of different patterns of (high/low) outdoor conditions. Also, solar radiation was measured for outdoor conditions, with a maximum solar radiation of 890 W/m$^2$ reached between 11:00 am and 1:00 pm. Solar radiation creates a temperature gradient inside the chimney air cavity that causes the driving force of air inside the chimney under the effect of stack effect.

The average solar brightness in Assiut was 12.125 h/day [16]. This encourages applying the SCPC system in this area. The overall heat transfer coefficient of the building part is calculated based on the physical properties of materials available in the local market with the same properties as the materials used in the numerical model. **Table 1** shows the characteristics of building materials. The overall heat transfer coefficients of walls, floors and roofs are 2.60, 0.797 and 0.443, respectively. The window opening is oriented towards the south and the

| Building part | Material | Conductivity (kJ/h m K) | U-Value (W/m2 K) | Thickness (m) |
|---|---|---|---|---|
| Glass windows | Single glass | — | 5.68 | 0.004 |
| External walls | Common plaster + cement (coating) | 1.26 | 2.60 | 0.02 |
| | Brick | 3.60 | | 0.10 |
| | Common plaster + cement (coating) | 1.26 | | 0.02 |
| Roof | Insulation | 0.2 | 0.443 | 0.05 |
| | Concrete slab | 4.2 | | 0.12 |
| | Cement plaster (coating) | 4.50 | | 0.01 |
| Ground | Floor | — | 0.797 | 0.10 |
| | Insulation | 0.2 | | 0.02 |
| | Concrete | 4.2 | | 0.10 |

**Table 1.** Description of building materials used.

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**Figure 2.** The outer view of the room with SCPC system fixed on its roof.

door opening towards the north. **Figure 2** shows the outer view of the room with the SCPC system on its roof.

The walls of the building are made from hollow clay bricks 0.1 m thick and covered with cement from both sides with thicknesses 0.02 m and a U-value of 2.6 (W/m$^2$K) for the wall. The ceiling is made from 0.12 m thick concrete and covered with 0.01 m thick cement on the inner side. The ceiling is covered by insulation and concrete cover with thicknesses 0.15 and 0.07 m, respectively, as shown in **Figure 3**.

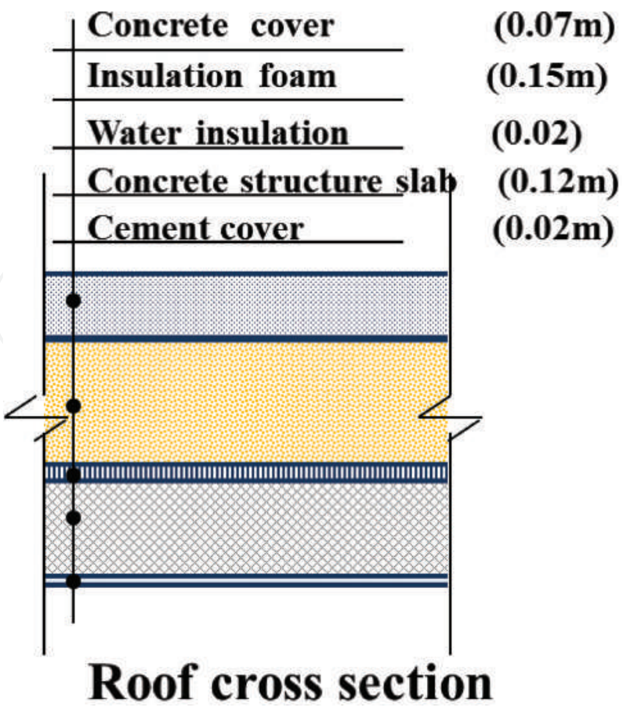


**Figure 3.** The description of roof layers and their thicknesses.

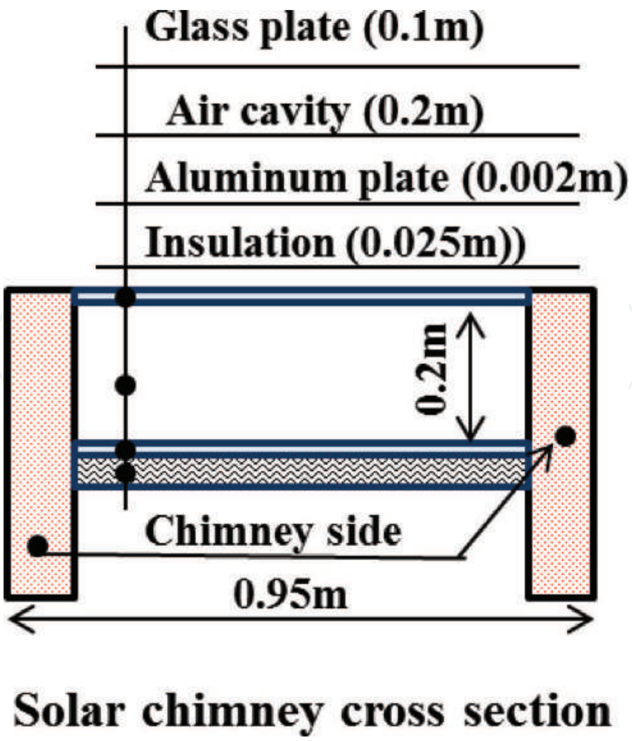


**Figure 4.** Cross section of the solar chimney cross section.

A thermal insulation, 0.1 m thick, is installed inside the floor layer to examine the performance of the integrated SCPC system for indoor thermal comfort while excluding heat effect from the ground. The SCPC system consists of two components: the solar chimney and the short wind tower. The solar chimney was fixed on the roof of the room facing south. The SCPC system is made from widely available and conventional materials in the Egyptian market. The solar chimney is made from black aluminum with emissivity 0.95 and glass with transmissivity 0.84 and thicknesses of 0.002 m and 0.1 m, respectively, as shown in **Figure 4**. Performance of the solar chimney was examined in the first phase. The maximum airflow rate in the chimney was 0.69 kg/s during a high solar radiation of 890 W/m$^2$ [17, 18].

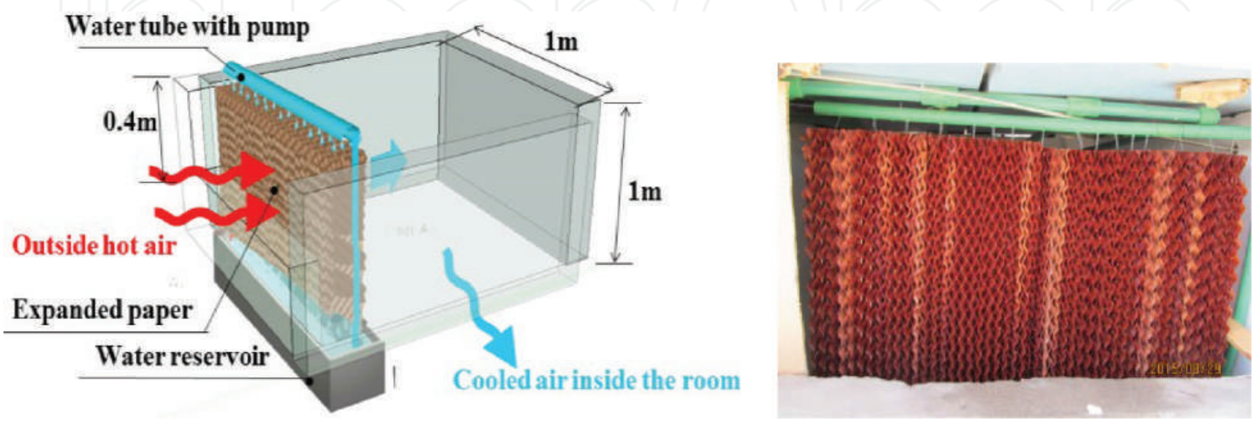


**Figure 5.** The description of evaporative technique in the wind tower made from expanded paper with water droplet from upper side.

The passive cooling technique was integrated inside the short wind tower with the opening facing north. The method applied in this study will depend on cooling the interior space envelope using cheap and local cooling materials without consuming much energy. The tower was built with dimensions 1 m x 1 m x 1 m (L × W × H). The wet pad in wind tower is made from 0.1-m thick expanded paper. A water tube was installed on the top of the expanded paper with small nozzles. A water pump is used to recirculate water from the water reservoir in the bottom of the pad. Water is supplied from the water tank to the bottom water reservoir using a concentric floating valve. It opens when the level of water in the bottom reservoir decreases as shown in **Figure 5**.

In order to understand the actual indoor environment after using the passive cooling system, a sample data will be presented from 2-month data monitoring as an example.

## 3. Comfort ventilation

Comfort ventilation is the important factor that deals directly with the human body and depends on the strategy used. It is based on the theory that high airspeed around the human body accelerates the skin's evaporation rate and, accordingly, improves the heat dissipation from the human body. This in turn shifts up the comfort upper level by providing such direct physiological cooling effect and decreases human discomfort due to skin wetness and the high humidity level [20]. In comfort ventilation strategy, two different impacts of the air velocity of the human body were determined: first, the heat exchange of the body that happens with convection; second, the evaporative capacity of the air. According to ASHRAE Standard 55 for naturally ventilated buildings, the acceptable thermal environment of indoor operative temperature ranges between 22°C and 28°C, and the comfort indoor air velocity of 1.6 m/s can be beneficial for improving comfort at higher temperatures [19]. So, new residence must have the acceptable thermal environment for all occupants. According to ASHRAE Standard 62–2001, ventilation rates depend upon the floor area, whereas the minimum ACH was 0.35, but no less than 15 CFM/person [21]. Also, passive natural ventilation standards require a minimum of three air changes for residential buildings. Finally, the comfort ventilation can easily be enhanced by appropriate building design and the system used.

## 4. Solar radiation and surface temperature analysis

**Figure 6(a)** shows the variation of daily solar radiation over time. A maximum solar radiation of 890 W/m$^2$ was reached between 11:00 am and 1:00 pm. Solar radiation creates a temperature gradient inside the chimney air cavity, and the warm air is less dense than cool air so it rises and creates a difference in pressure which in turn induces air movement, causing the driving force of air inside the chimney under the effect of stack effect. The main component of the solar chimney is the absorber plate, which was made of an aluminum plate painted black with 0.95 emissivity. A wind-driven protection was used at the top in order to avoid reverse flow. It is clear that the maximum surface temperature of aluminum was 86°C at 1:30 pm due to high

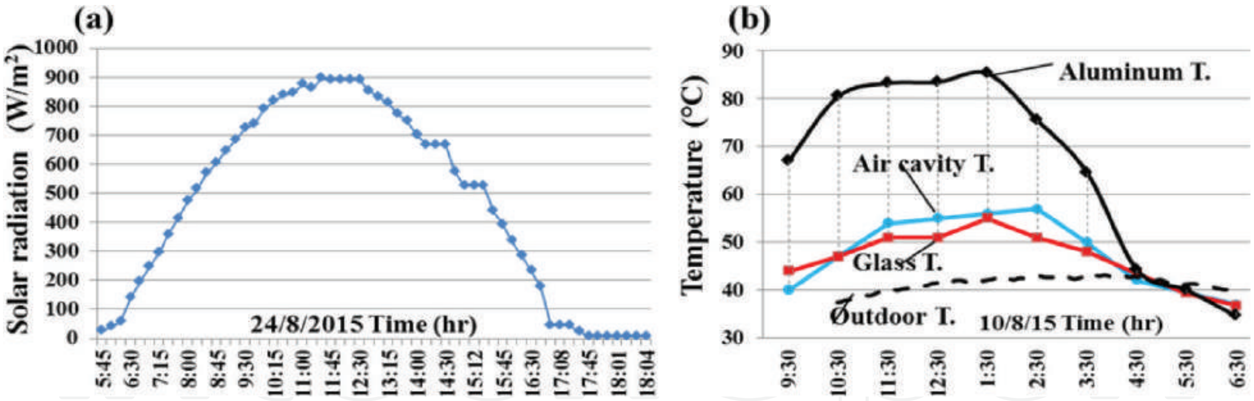


**Figure 6.** (a) The variation of daily solar radiation over to time. (b) The variation of different temperatures with time.

intensity of incident solar radiation in this period. Temperature was recorded in the middle of the aluminum plate. After midday, temperature started to decrease until 65°C at 3:30 pm, followed by a sharp drop of temperature due to decrease of solar intensity and high heat release without any thermal storage integrated with the aluminum plate. Also, glass surface temperature has the same pattern as aluminum temperature with 15°C higher than outdoor temperature. This affects air cavity temperature strongly. This finding is in agreement with [22].

**Figure 7** shows the temperature profile of outlet air inside the chimney cavity. It is clear that the temperature of the chimney cavity increases and reaches 48°C for the highest temperature at 12:00 pm with high solar radiation. The temperature of air cavity is higher than outdoor until 4:00 pm. Then, a strong reduction of air temperature inside the cavity was reached. This is due to the decrease of aluminum surface temperature and heat release from the absorber. **Figure 4** shows the thermal images of outside chimney glass plate with the highest three temperature points on its surface at 12 pm on 13/8/2015.

**Figure 8** shows the temperature distribution of three points on the upper side of the solar chimney (glass surface temperature) with an average temperature of 38°C and 36°C at 1:00 pm and 3:00 pm, respectively, due to high solar intensity. The thermal gradient of chimney surface temperature and aluminum surface temperature strongly affects the airflow through the chimney.

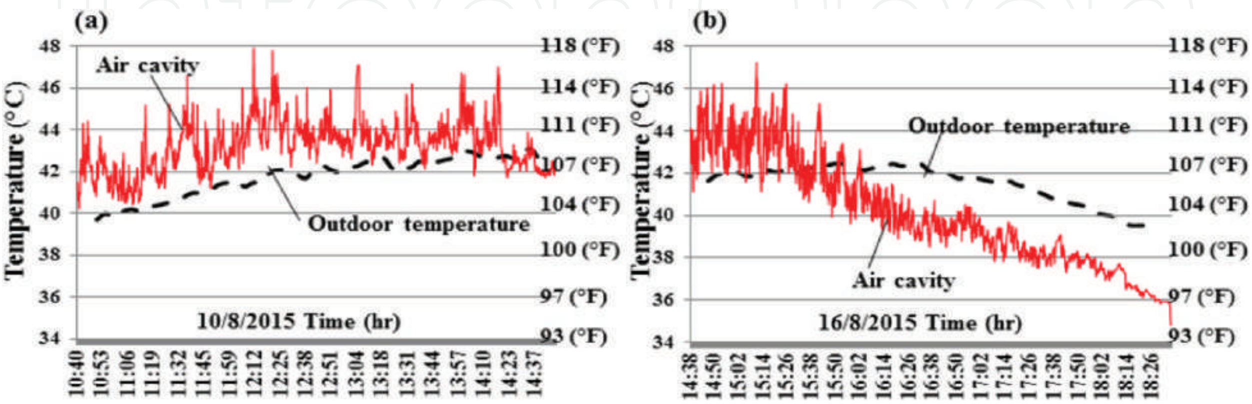


**Figure 7.** (a) Temperature profile of outlet air inside the chimney cavity from 10:00 am until 14:45 pm. (b) Temperature profile of outlet air inside the chimney cavity from 14:38 am until 18:30 pm.

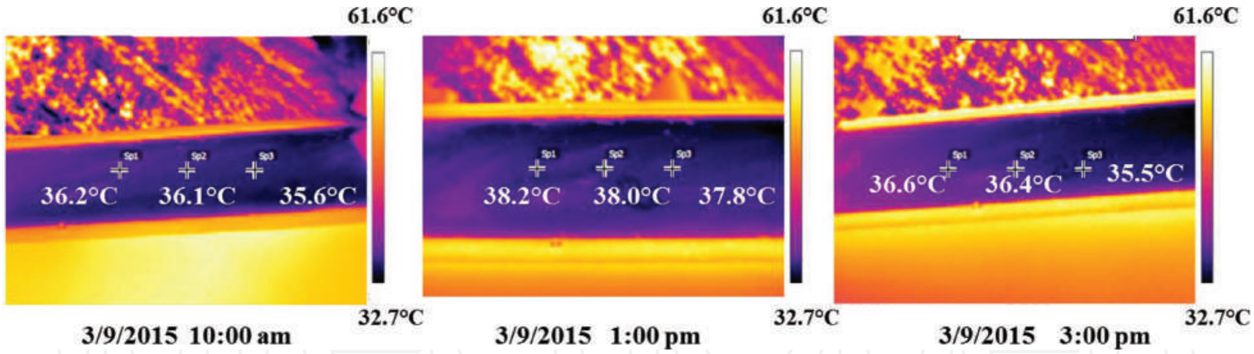


**Figure 8.** The variation of glass surface temperatures in the solar chimney.

Validation was done for the numerical simulation with the experimental results. The detailed model for the numerical calculation was studied, including boundary condition, geometry and material physical properties [7]. Results of chimney air temperature, cooling tower inlet temperature and aluminum surface temperature with the help of the analytical model were found in good agreement with the corresponding experimental values. The experimental results tend to be higher than analytical model by about 2% and 2.5% in average. However, the airflow at the chimney is higher than analytical model by about 40%. This indicates that the presence of outdoor high wind speed and pressure coefficient on building surfaces and chimney outlets increases airflow rate of the stack effect with a negative effect of reverse flow that occurs in the chimney for some time and decreases performance of the evaporative pad with an average difference of 6% for the indoor temperature.

Due to the buoyancy force, the outer hot air passed through the expanded paper with water droplet, and then the outdoor air temperature was reduced inside the wind tower after passing through the wet pad. A graph indicating a typical variation of indoor cooling using a cooling medium is shown in **Figure 9**. The air temperature inside the room increased gradually due to the presence of occupants inside the room and heat gained by the building. Also, the temperature inside chimney air cavity is decreased gradually due to the absence of thermal storage attaching to the aluminum plate when solar irradiation decreases gradually. Therefore, the air temperature increases in the chimney air cavity, corresponding to the increase of solar radiation.

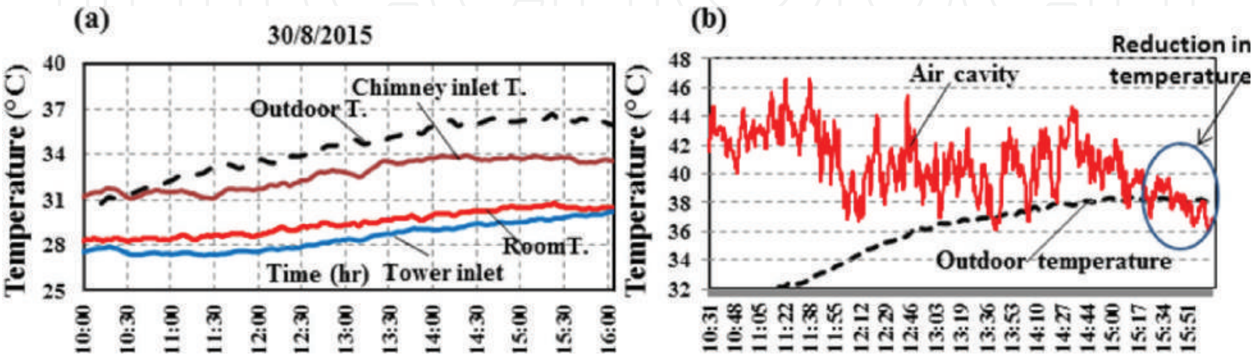


**Figure 9.** (a) The variation between tower inlet temperature, room temperature and chimney inlet temperature based on the cooling effect. (b) The temperature difference between chimney air cavity and outdoor temperature.

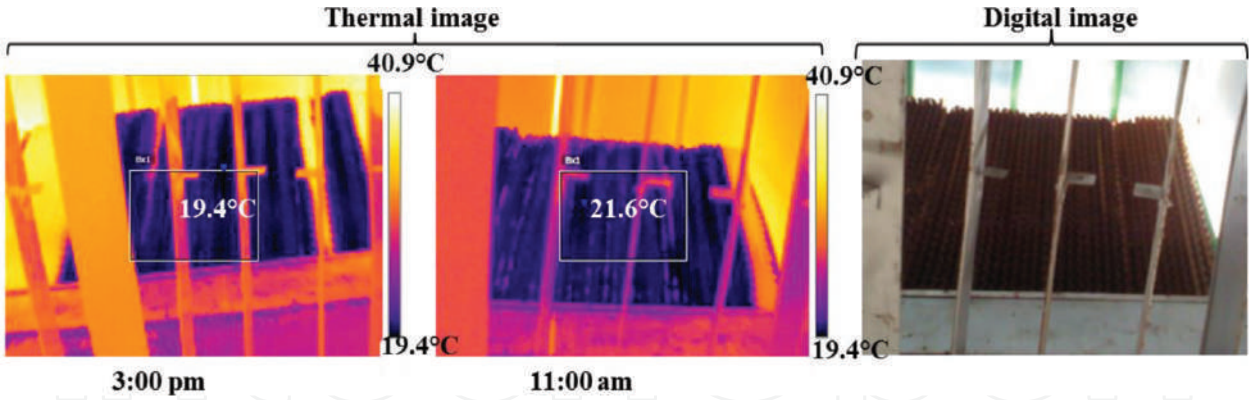


**Figure 10.** The variation of expanded paper surface temperatures (cooling pad).

**Figure 10** shows that the minimum surface temperature of the expanded paper (cooling pad), with water droplet, was 19.4°C at 3:00 pm with an average wet bulb temperature of 22°C. The decrease of surface temperature of cooling pad strongly affects airflow temperature and causes reduction of outdoor air temperature with constant enthalpy. This demonstrates the concept of evaporative cooling. The average water consumption is 16 l/day. This is because the outdoor air that flows through the pads is cooled to a temperature close to the WBT. Then, the indoor air of the building, cooled by an evaporative cooling system, is further heated by about 1–3°C above the output air from the evaporative cooling system, depending on the airflow rate of evaporative cooling and indoor heat gained by the building. This finding is in agreement with [23, 24]. Energy consumption for this system is 18 W only.

## 5. Thermal comfort and $CO_2$ evaluation according to ASHRAE and ACS

It is observed that most of the outlet air temperatures from the wind tower are below the upper limit of the 90% acceptable range, as shown in **Figure 11**. The temperature of the outside air that passes through the wet medium can be reduced significantly with a difference 6 K ~ 7 K. Only 10% of the measured data exceeded the upper limits. **Table 2** shows the statistical analysis for indoor temperatures with a statistically significant difference = 0.024 (p level < 0.05). Therefore, the supplied air is still considered suitable to enhance indoor thermal comfort. The maximum indoor temperature was reached at 6:00 pm with a long time lag between outdoor and indoor temperatures. This is due to the effect of indoor thermal mass that impacts room cooling. This is in agreement with [23]. Reducing indoor temperature is based on the amount of water that passes inside the wet pad and the number of nozzles in the water tube.

Humidity is strongly affected by cooling the wet medium. It is observed that indoor relative humidity after using passive cooling did not rise above 57% during daytime and most of the time was below 50%, indicating that further cooling is needed. **Figure 12** shows that

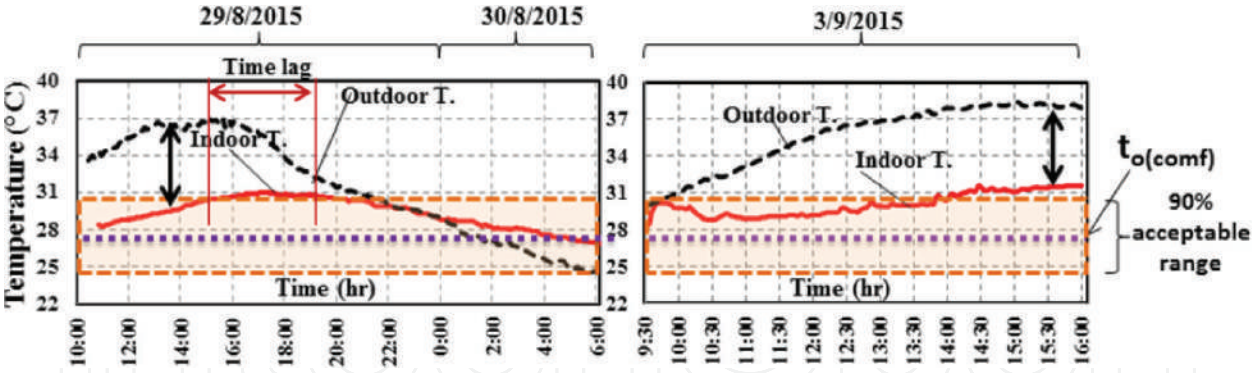


**Figure 11.** Temperature profile for indoor environment with a cooling technique compared to outdoor condition on the 90% acceptable range of adaptive comfort standard.

| Indoor temperature | Range | Mean ± SD | Sample distribution | |
|---|---|---|---|---|
| | | | Skewness | Kurtosis |
| | 28.3–31.7 | 30.1 ± 0.86 | −0.63 | −1.01 |

**Table 2.** The statistical analysis of indoor temperature.

room relative humidity is located within the acceptable range of relative humidity 20%~60%, according to ASHRAE Standard 2004 [19]. Arundel concluded that the optimum humidity level for minimizing adverse effects for health is between 40 and 60% [25]. Also, most of the investigated cases were very close to the summer comfort zone. This is because the air outside is so dry, typically below 10% relative humidity during daytime.

The concentration of $CO_2$ inside the experimental room is very low. The average concentration is 550 ppm, with three occupants staying inside the room. The lower concentration inside the room

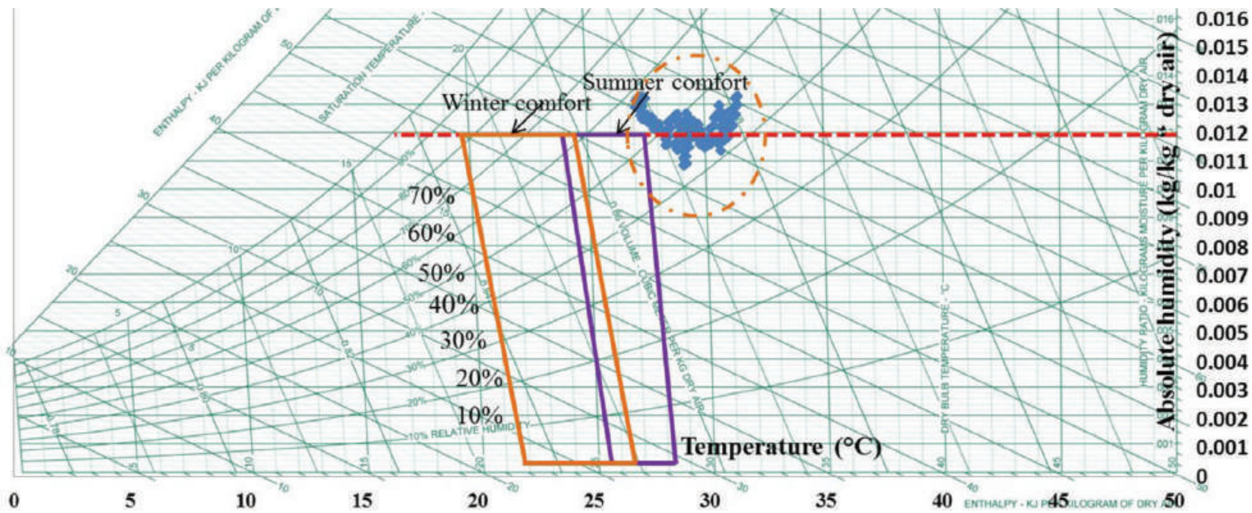


**Figure 12.** Temperature and humidity conditions inside the room after using the SCPC system.

is due to high airflow rate in the chimney and wind speed to a maximum of 0.69 kg/s, which affects $CO_2$ concentration. This helps improve the indoor air quality and achieve a safe environment according to [22]. **Figure 13** shows the variation of indoor carbon dioxide concentration.

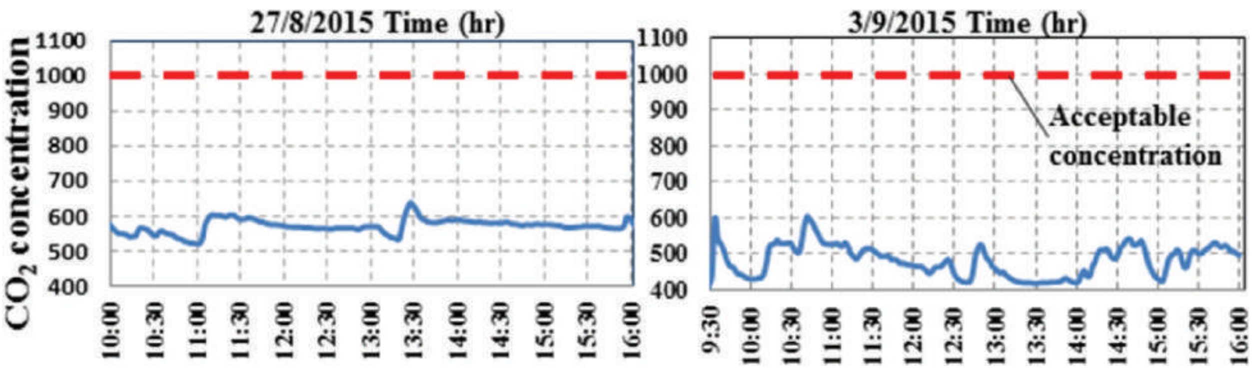


**Figure 13.** Indoor $CO_2$ concentration inside the room with SCPC system.

## 6. Conclusion

Using the SCPC system provides many advantages for indoor environments and achieves energy saving for cooling inside indoor room environments of hot arid regions. It is concluded that the airflow rate through a solar chimney system is greatly affected by the pressure difference between openings caused by temperature across the chimney surface. The results indicate that using the SCPC system reduced indoor temperature to be within the 90% acceptable comfort range. The SCPC system is considered a passive cooling air conditioning system that achieves a significant reduction of indoor temperature between 6 and 7 K based on the condition of the wet pad. The findings from the experimental and numerical calculations were in good agreement. Installation of the solar chimney parts and building the short wind tower are based on the available and conventional materials in the Egyptian market. The results of this research will be used to develop a new cooling system for low energy consumption (only 18 W for the water pump). The new cooling system is made of local materials and provides fresh cooled air with good indoor air quality. The materials of the system have high durability and made from normal glass, aluminum plate and standard brick for the tower. These materials are available at the local market and need simple modification in the ceiling structure of the upper flat. The system structure and materials need no specific manufacturing technology. The operation cost for the system is very low as it depends on solar radiation only. The 0.1-m thick evaporation pad in the tower can be changed nearly every 5 years with simple cleaning required every summer. This new cooling system can be integrated in the housing projects (National Housing Authority) of low-income people in new and existing cities. Adopting this system makes a significant improvement in building energy conservation.

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