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ENERGY SYSTEMS AND ENVIRONMENT

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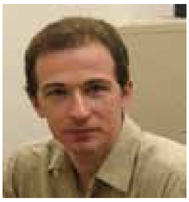
Meet the editor



Dr. Pavel Tsvetkov is an associate professor in the Department of Nuclear Engineering, Texas A&M University. His research efforts are focused on novel energy systems meeting the globally growing need for sustainable resources. System design and optimization methods for complex engineered systems enable development of advanced sustainable nuclear energy technologies towards "environmentally benign" system designs and their deployment. The integrated systems approach of Dr. Tsvetkov's research program makes it possible to holistically optimize choices for the system. Dr. Tsvetkov is a member of ANS, ASME, ASEE, Alpha Nu Sigma, and Phi Kappa Phi. Dr. Tsvetkov and his students have published over 340 papers in peer-reviewed journals, conference proceedings, technical reports, and books.

Contents

Preface

Our contemporary society is an energy consumer. We need energy to enhance, maintain, and improve our quality of life locally and globally, as well as literally and philosophically. We consume energy and resources at an exponential rate. At the same time, our society is really dependent on the sustainability of both energy and resources. Thus, it is of paramount importance for our wellbeing and long-term prosperity to balance our consumption and production as far as energy and vital resources such as water and air are concerned. This simple consideration brings us to the key idea of this book—to explore relationships between energy systems and our environment.

We need energy for our safety and security. To provide needed energy resources, we need energy sources and power plants to take advantage of them and to use them for our needs. This book looks at environmental aspects of energy technologies, from common traditional sources in use, new sources, and emerging sources and technologies.

We do not have all the answers and solutions but with this book we would like to support our quest for answers to questions such as: Do we have enough energy? What will future energy sources look like? Are we energy and environmentally sustainable if our energy demands are to be met? and many other key energy and resource questions.

The objective of this book is to serve as a one-stop comprehensive information resource on energy and environment topics, from energy science to energy engineering to energy politics. Starting with science and technology topics we link them to economics and politics showcasing interconnections between energy sources, energy utilization, energy conversion, and sustainability under the common theme of energy and environment.

The chapters of this book cover all energy sources and technologies, their current and future status, and discuss challenges, opportunities, and expectations from use and environmental points of view. The book achieves its objective by offering and integrating deeply technical and socioeconomics papers together on energy and environment topics.

The authors and the editor hope to facilitate the research into environmentally sustainable energy technology accounting for use and impact. Readers will find stimulating thought-provoking information on energy and environment that does not favor any one source of energy but supports our quest for energy while making sure our planet is capable of sustaining us.

Do you think we will always have enough energy to sustain the Earth? The chapters of this book will engage you in discussions contributed by authors with a wide variety of views.

Finally, I would like to express my sincere appreciation to the InTech team who made this book possible. Especially, our thanks go to Ms. Anita Condic, Author Service Manager, for her guidance and all the help in the process.

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Section 1

Energy Resources

Chapter 1

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

Joseph Nyangon and John Byrne

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].

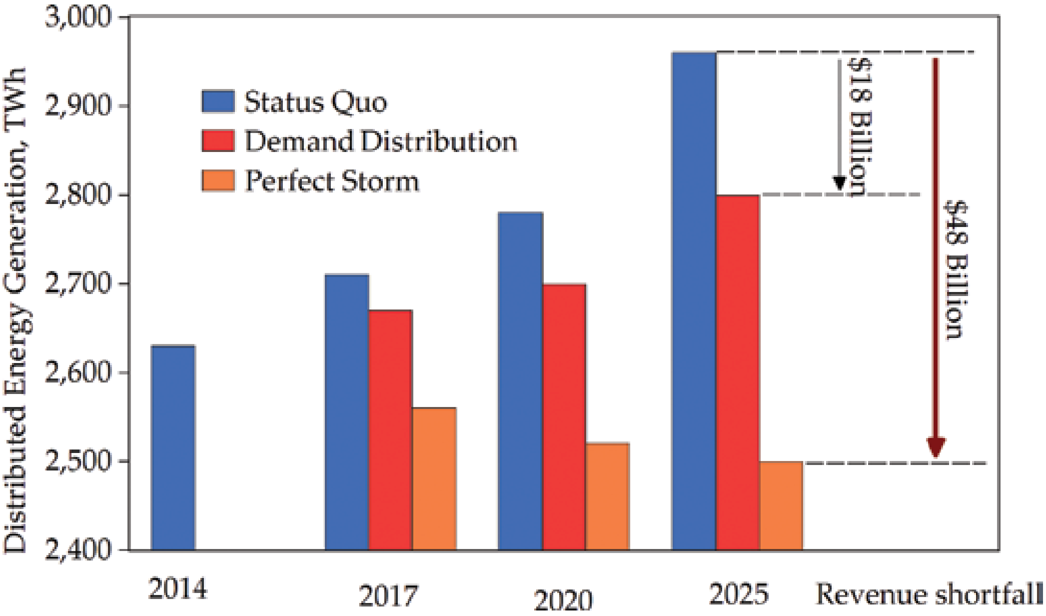

Figure 1. Estimated erosion of utility revenue.

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,

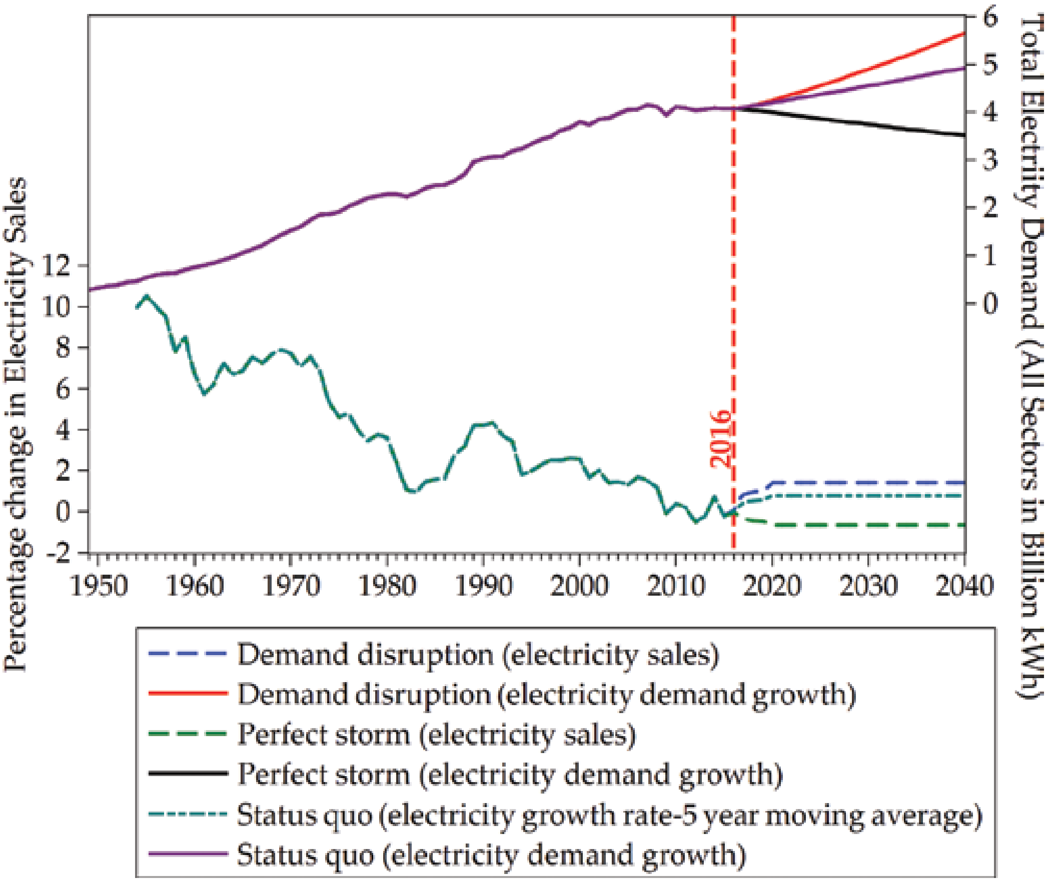

Figure 2. How the adoption of energy demand-disrupting technologies could erode energy demand and utilities' revenues through 2040.

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

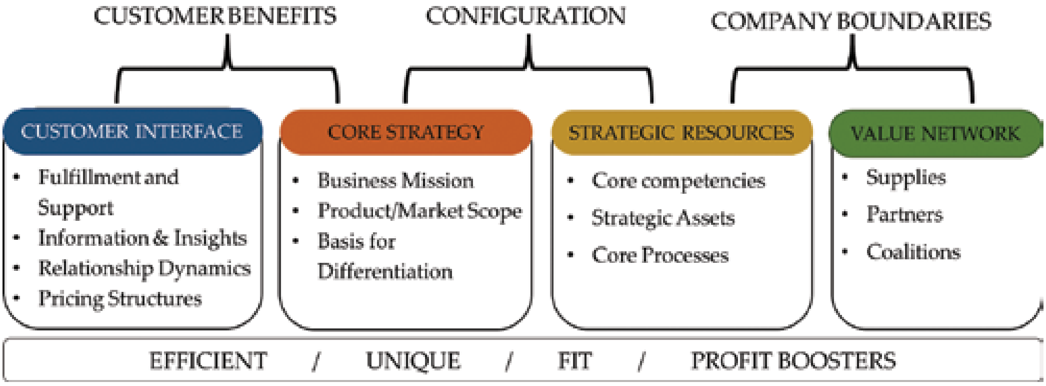

Figure 3. Components of Hamel business model framework.

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.

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. 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. Emphasizes enhanced customer-centric paradigm (e.g., billing solutions for effective management). Nonlinear transactions.
Value network	Includes utility added values or business offerings to resource providers, suppliers, and partners.	Removes market barriers and promotes distributed utilities. 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. 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. Energy efficiency savings are part of utility revenue not dedicated surcharge. Earning impact mechanisms (EIM) replace platform service revenues (PSR) and market based earnings (MBE). Includes modified clawback mechanisms to attract third parties. Encourages time of use (TOU) rates. 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

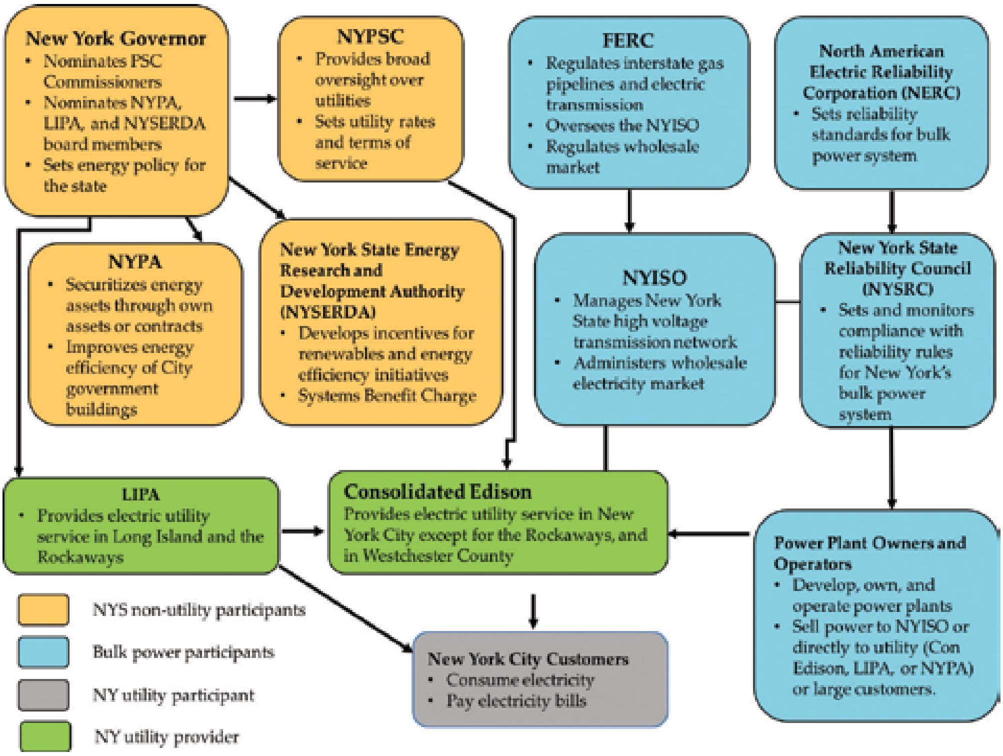

Figure 4. NYS electric industry participants and institutions.

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].

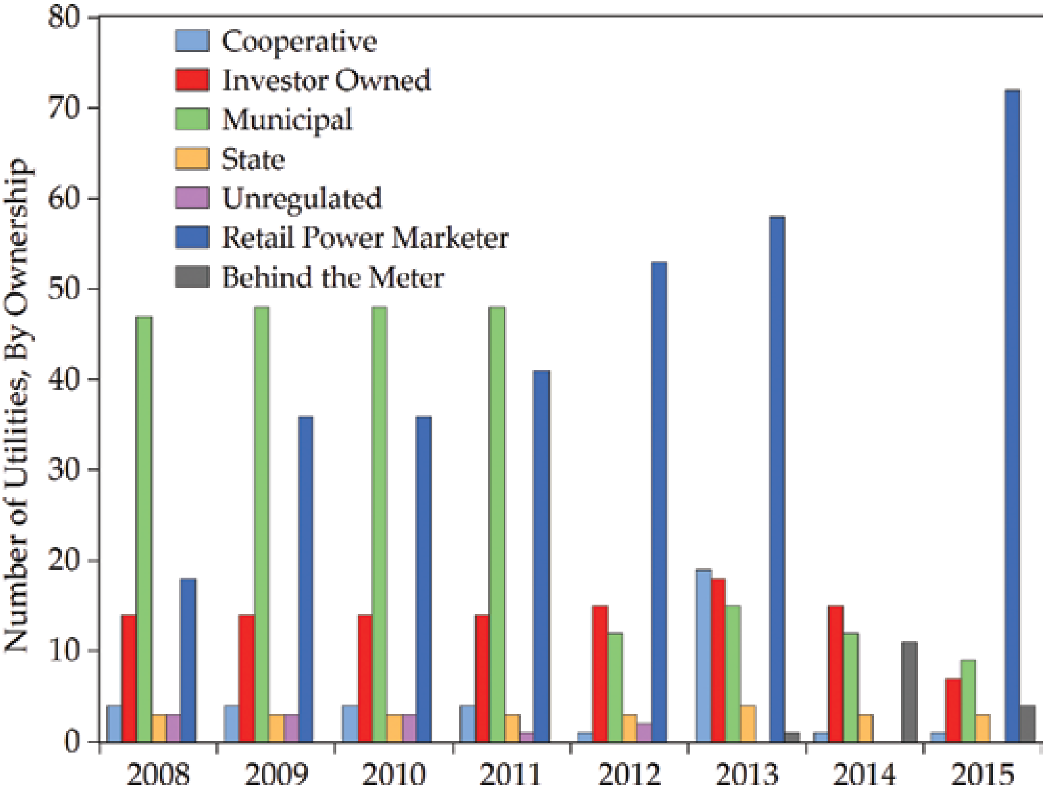

Figure 5. Number of utilities, by ownership from 2008 to 2015.

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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No potential conflict of interest was reported by the authors.

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Chapter 2

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,

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[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

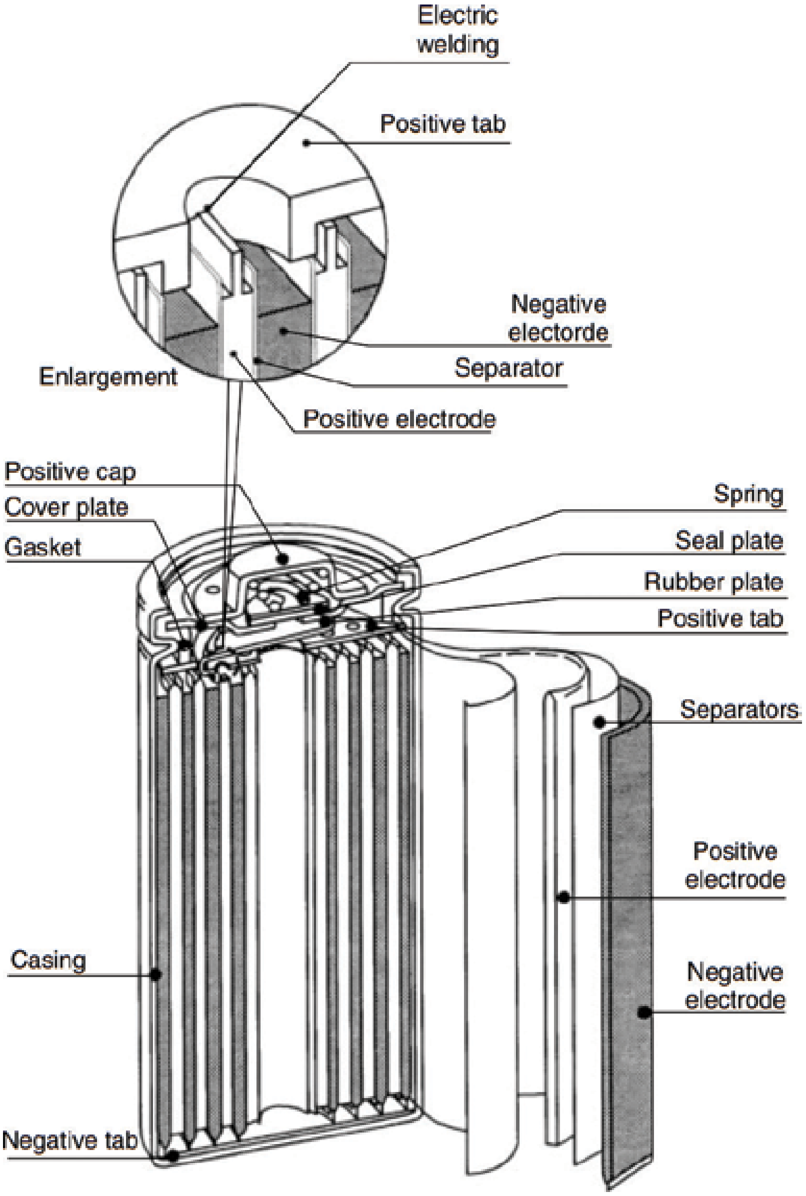

Figure 1. Internal structural design of a cylindrical Ni-cd battery [6]. Copyright Wiley-VCH Verlag GmbH & co. KGaA. Reproduced with permission.

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 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].

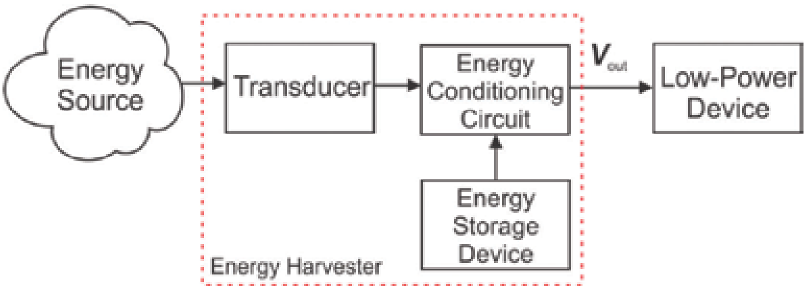

Figure 2. Basic structure of an energy harvesting system.

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.

- **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 ΔT 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 ΔT. 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, ΔT 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.

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[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.

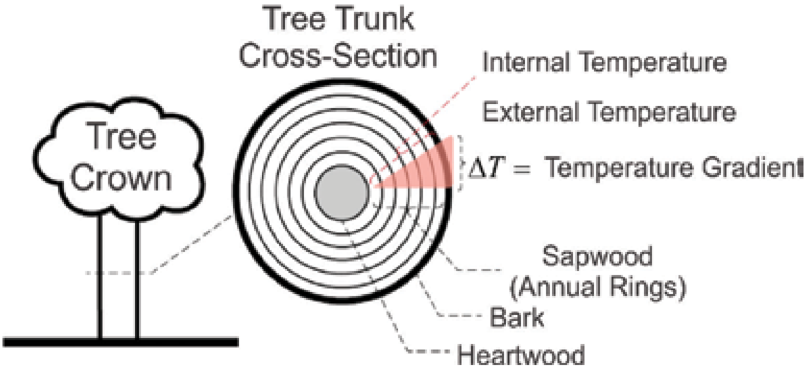

Figure 3. Temperature gradient comes from different annual rings related to external temperature [13].

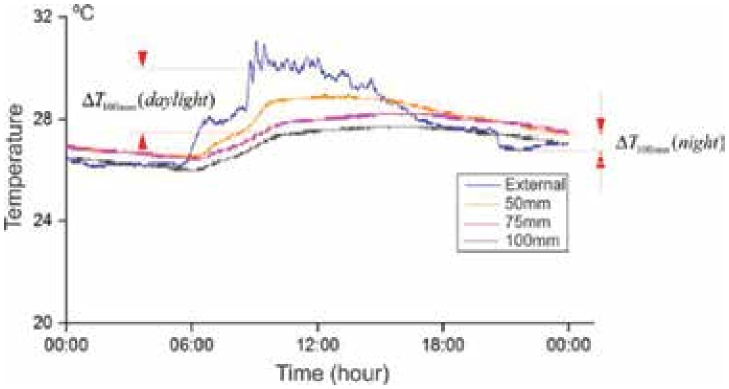

Figure 4. Temperature measurement in three depths of a tree: 100, 75 and 50 mm and the external temperature.

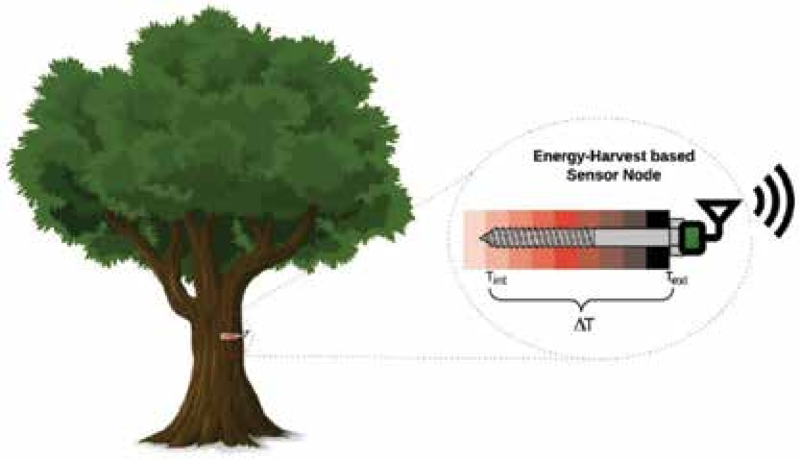

Figure 5. A possible implementation of the tree trunk energy harvesting transducer.

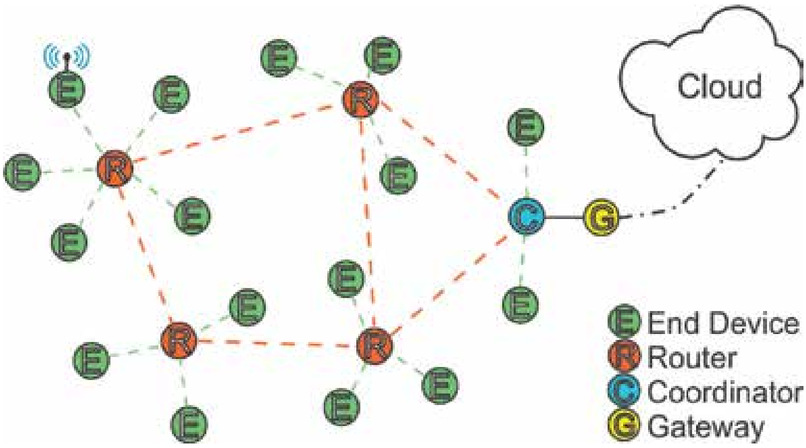

Figure 6. Typical wireless sensor networks.

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 multi-hop/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

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[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.

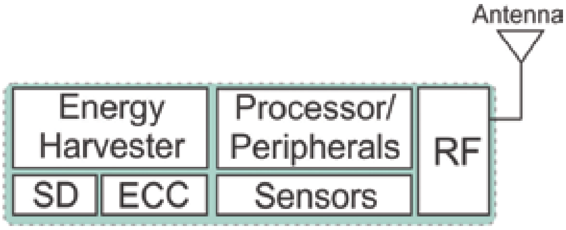

Figure 7. IoNaT node. SD: Energy storage device. ECC: Energy conditioning circuit. RF: RF transceiver.

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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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

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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

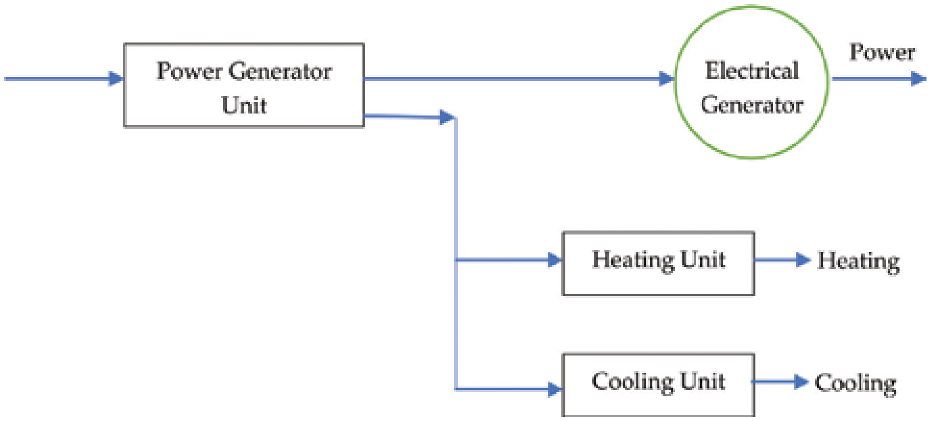

Figure 1. Schematic of a typical CCHP system.

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

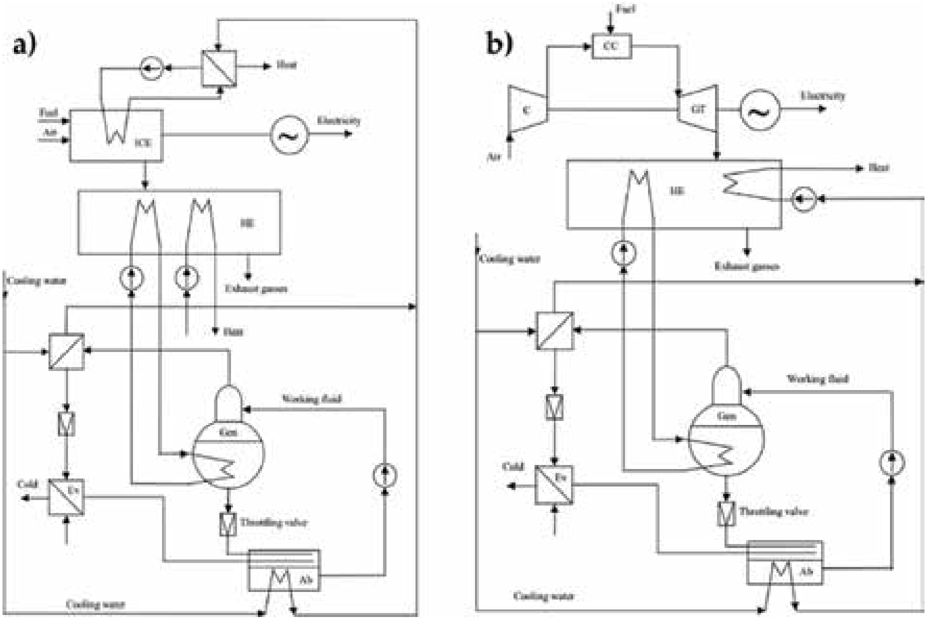

Figure 2. Simplified scheme of a trigeneration plant with (a) internal combustion engine with absorption chilling machine and (b) gas turbine with absorption chilling machine [23].

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].

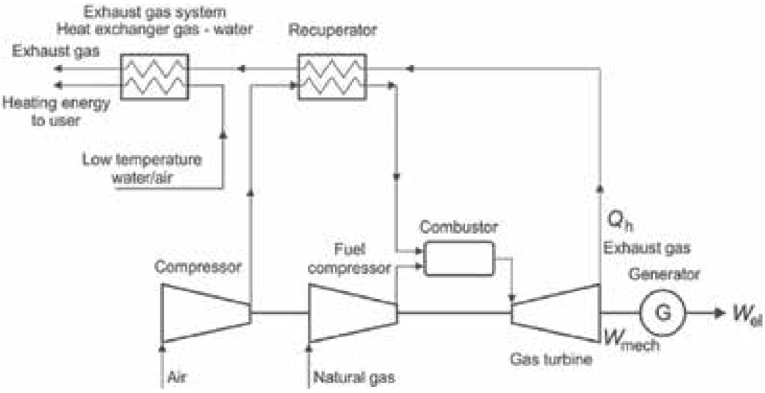

Figure 3. CCHP system design with a microturbine as a basic aggregate [21].

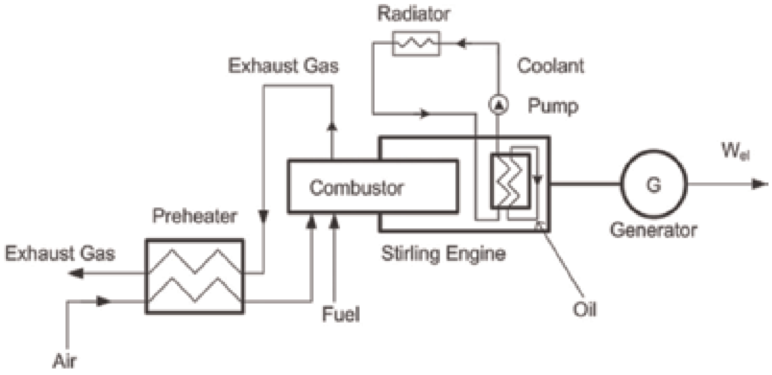

Figure 4. CCHP system design with the Stirling engine as a basic aggregate [21].

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).

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

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

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

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, ξ 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

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

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	$EF_{elec,NX}$	1.12×10^{-5}	kg/kWh
Natural gas NO_x emission	$EF_{NG,NX}$	8.54×10^{-7}	kg/kWh
Electric CH_4 emission	$EF_{elec,M}$	8.26×10^{-6}	kg/kWh
Natural gas CH_4 emission	$EF_{NG,M}$	1.17×10^{-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

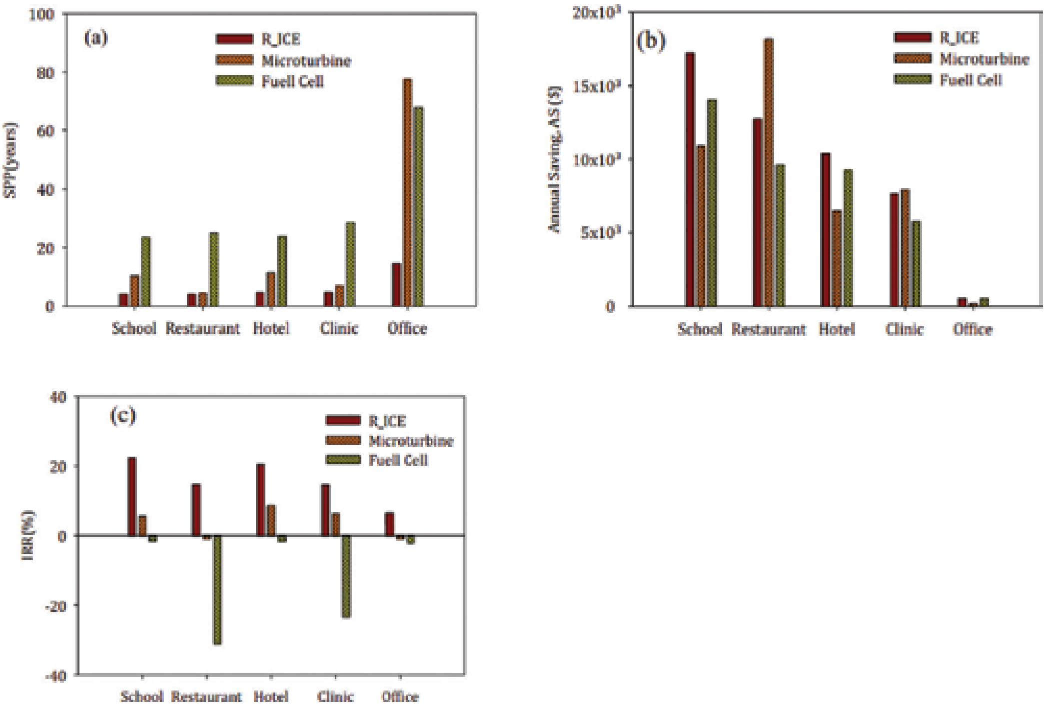

Figure 5. (a) *SPP*, (b) *AS*, and (c) *IRR* comparison of CCHP installed building types with the reference building [32].

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.

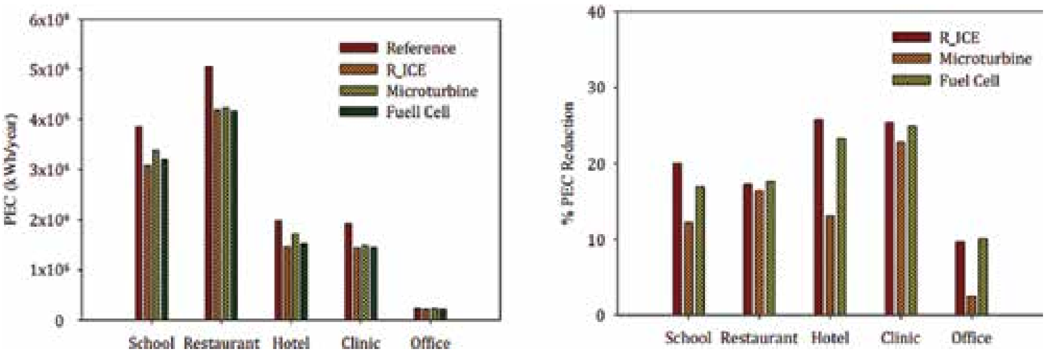

Figure 6. PEC comparison of CCHP installed building types with the reference building in Minneapolis, MN [32].

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.

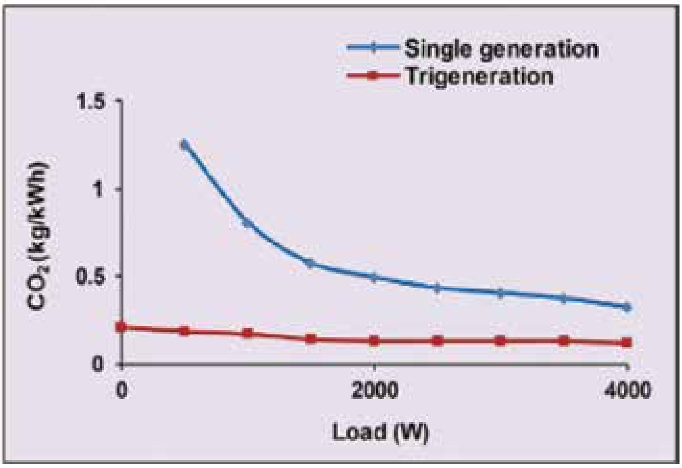

Figure 7. Sample of variation of carbon dioxide with load [34].

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

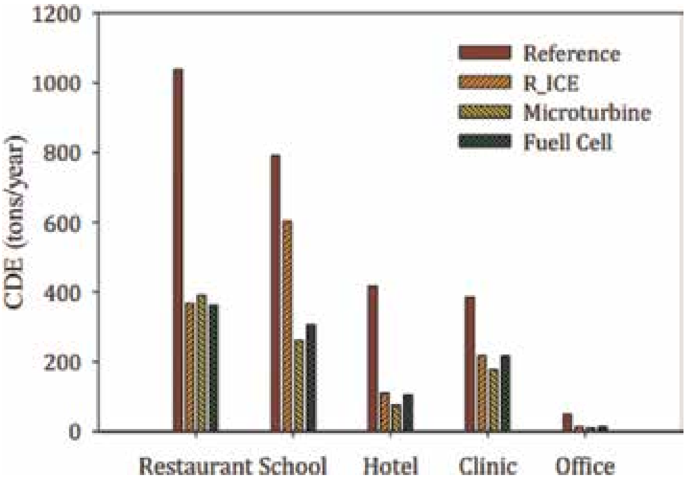

Figure 8. CO_2 emissions of reference building compared with CCHP installed different building types in Minneapolis, MN [32].

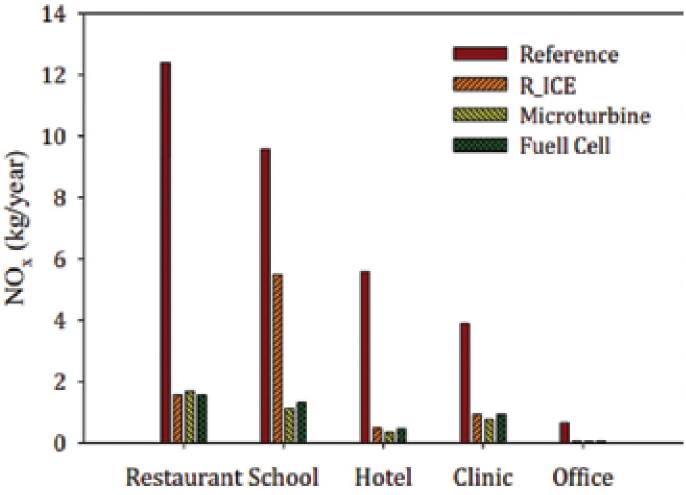

Figure 9. NOx emissions of reference building compared with CCHP installed different building types in Minneapolis, MN [32].

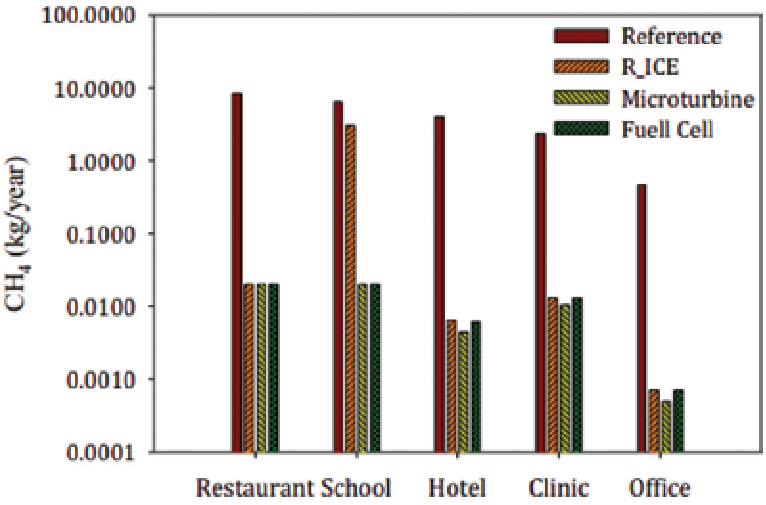

Figure 10. CH_4 emission of reference office building compared with CCHP installed building in Minneapolis, MN [32].

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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Section 2

Energy Conversion

Chapter 4

Exergy Flows Inside Expansion and Compression Devices Operating below and across Ambient Temperature

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Additional information is available at the end of the chapter

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Abstract

The various definitions of the coefficient of exergy efficiency (CEE), which have been proposed in the past for the thermodynamic evaluation of compression and expansion devices, operating below and across ambient temperature as well as under vacuum conditions, are examined. The shortcomings of those coefficients are illustrated. An expression for the CEE based on the concept of transiting exergy is presented. This concept permits the quantitative and non-ambiguous definition of two thermodynamic metrics: exergy produced and exergy consumed. The development of these CEEs in the cases of an expansion valve, a cryo-expander, a vortex tube, an adiabatic compressor and a monophasic ejector operating below or across ambient temperature is presented. Computation methods for the transiting exergy are outlined. The analysis based on the above metrics, combined with the traditional analysis of exergy losses, allows pinpointing the most important factors affecting the thermodynamic performance of sub-ambient compression and expansion.

Keywords: exergy efficiency, expansion, compression, sub-ambient, across ambient

1. Introduction

Cooling is part of twenty-first century life. Air conditioning, food conservation, industries such as steel, chemicals, and plastics depend on cooling. By mid-century people will use more energy for cooling than heating [1]. Almost all cold is produced by vapor-compression refrigeration and requires large amounts of electricity for its production. And since electricity is still overwhelmingly produced by burning fossil fuels, the rise in cold production will inevitably increase both fuels consumption and power plant emissions. A climate-change irony is that cooling makes the planet hotter. Besides the development of new cooling devices using renewable energy, an important way to reduce refrigeration power consumption is through the energy efficiency improvement of vapor-compression cycles and their associated elementary processes. The processes of compression and expansion play a central role in air-conditioning, refrigeration and cryogenics. An important question still remains: How to define the efficiency of these processes by taking into account the constraints of the first and second laws of thermodynamics? The answer will be discussed in this paper.

The introduction of exergy, the thermodynamic function that takes into account the quality as well as the quantity of energy, has paved the way for a unified approach to the concept of efficiency, a subject pioneered by Grassmann [2]. Serious difficulties concerning the practical application of this concept to sub-ambient systems, however, retarded the acceptance of exergy analysis by the air-conditioning and refrigeration engineering profession. One can mention, in particular, the difficulty of formulating a coefficient of exergy efficiency (CEE) for elementary processes such as compression and expansion. The coefficient should evaluate the exergy losses, quantify the extent to which the technical purpose of an elementary process is achieved, as well as quantify the exergy consumption within the process. Finally, a uniquely determined value (not several) should be assigned to the coefficient. This paper examines some important points pertinent to these issues and presents a definition of the CEE for the thermodynamic evaluation of expansion and compression devices operating below and across ambient conditions. The definition is based on the concept of transiting exergy, introduced by Brodyansky et al. [3], that allows non-ambiguous computation of two metrics: exergy produced and exergy consumed.

2. Basic concepts of exergy analysis of sub-ambient systems

The maximum amount of work obtained from a given form of energy or a material stream, using the environment as the reference state, is called exergy [4, 5]. Three different types of exergy are important for thermodynamic analysis of the sub-ambient processes: exergy of heat flow, exergy of work (equivalent to work) and thermo-mechanical exergy, also known as physical exergy by some authors [4, 6]. Chemical exergy [7], important for some refrigeration systems based on the mixing of streams of different composition, is not considered in the present paper.

2.1. Exergy of heat flow at the sub-ambient conditions

The exergy of heat flow $\dot{Q}$ [4] is defined as:

$$\dot{E}^{Q} = \dot{Q} \cdot \Theta \tag{1}$$

where $\Theta = 1 - T_0/T$ is the Carnot factor determined by the temperature T of heat flow, and the ambient temperature T_0. Contrary to conditions above ambient, Θ is negative for sub-ambient temperatures. However, according to Eq. (1), $\dot{E}^Q$ is positive due to the fact that heat is removed from a cooled object, and thus $\dot{Q}$ has a negative sign in Eq. (1). The energy and exergy balances of a reversible refrigerator (RR) are presented in **Figure 1**. One can notice that the directions of energy and exergy flows are opposite below T_0. This means that the exergy of a heat flow at $T < T_0$ is looked upon as a product of the refrigeration system rather than as feed. The exergy transfer of a RR characterizes the rate of transformation of power $\dot{W}$ to exergy of heat flow $\dot{Q}$ (exergy of produced cold). Given that the system presented in **Figure 1** is reversible, the minimum power $\dot{W}_{min}$ necessary to maintain a cooling rate $\dot{Q}$ equals $\dot{E}^Q$. Obviously it is not the case for a real (non-reversible) refrigerator, where $\dot{E}^Q$ is lower than $\dot{W}$ by the value of exergy losses $\dot{D}$.

2.2. Thermo-mechanical exergy

The thermo-mechanical exergy equals the maximum amount of work obtainable when the stream of substance is brought from its initial state to the environmental state, defined by pressure P_0 and temperature T_0, by physical processes involving only thermal interaction with the environment [3, 4]. The specific thermo-mechanical exergy $e_{P,T}$ is calculated according to:

$$e_{P,T} = [h(P,T) - h(P_0,T_0)] - T_0 \cdot [s(P,T) - s(P_0,T_0)] \tag{2}$$

The value of $e_{P,T}$ may be divided by two components: thermal exergy e_T due to the temperature difference between T and T_0, and mechanical exergy e_P due to the pressure difference between P and P_0. It is important to emphasize that this division is not unique, because e_T depends on pressure conditions and e_P in its turn depends on temperature conditions. As a result, the division has no fundamental meaning and leads, as will be illustrated further, to ambiguities for the exergy efficiency definition. By conventional agreement [4], e_T and e_P are defined as:

$$e_T = [h(P,T) - h(P,T_0)] - T_0 \cdot [s(P,T) - s(P,T_0)] \tag{3}$$

$$e_P = [h(P,T_0) - h(P_0,T_0)] - T_0 \cdot [s(P,T_0) - s(P_0,T_0)] \tag{4}$$

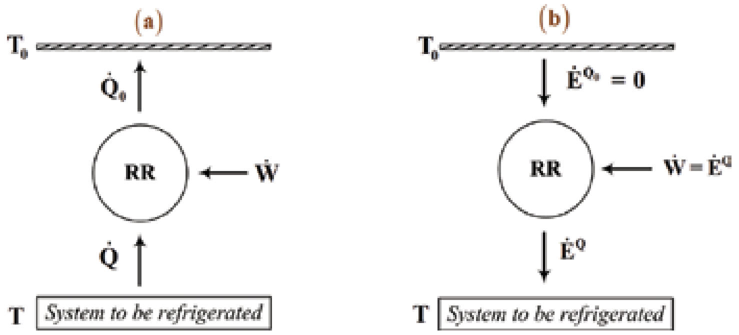

Figure 1. Energy (a) and exergy (b) balances of a reversible refrigerator (RR).

The contribution of e_T and e_P to the value of $e_{P,T}$ can be clearly visualized on the exergy-enthalpy diagram presented in **Figure 2**. For instance, the thermal exergy for point 1 is illustrated as the segment $(e_T)_1$ defined by the intersections of two isotherms T_1 and T_0 with the isobar P_1. The mechanical exergy for point 1 is illustrated as the segment $(e_P)_1$ defined by the intersections of two isobars P_1 and P_0 with the isotherm T_0. Whatever the temperature conditions are ($T < T_0$ or $T > T_0$), the thermal exergy is always positive [3], as clearly presented on the e-h diagram. In this sense the e_T behavior is similar to that of the exergy of heat flow, that is always positive, as has been discussed. Meanwhile, e_P is only positive for conditions $P > P_0$ (see for example point 1), but it is negative for $P < P_0$, as illustrated by point 2 in **Figure 2**.

2.3. Exergy efficiency of processes operating below and across the ambient temperature

The exergy balance around any process under steady state conditions and without external irreversibilities (the case considered in this paper) may be written as [4]:

$$\dot{E}_{in} = \dot{E}_{out} + \dot{D}_{int} \tag{5}$$

Here $\dot{E}_{in}$ and $\dot{E}_{out}$ are the inlet and outlet exergy flows; $\dot{D}_{int}$ is the rate of internal exergy losses. There is abundant scientific literature [3–9] on the subject of the exergy performance criteria definition based on Eq. (5). However, there are only a few definitions of this criteria applied to the processes of expansion and compression operating below and across ambient temperature.

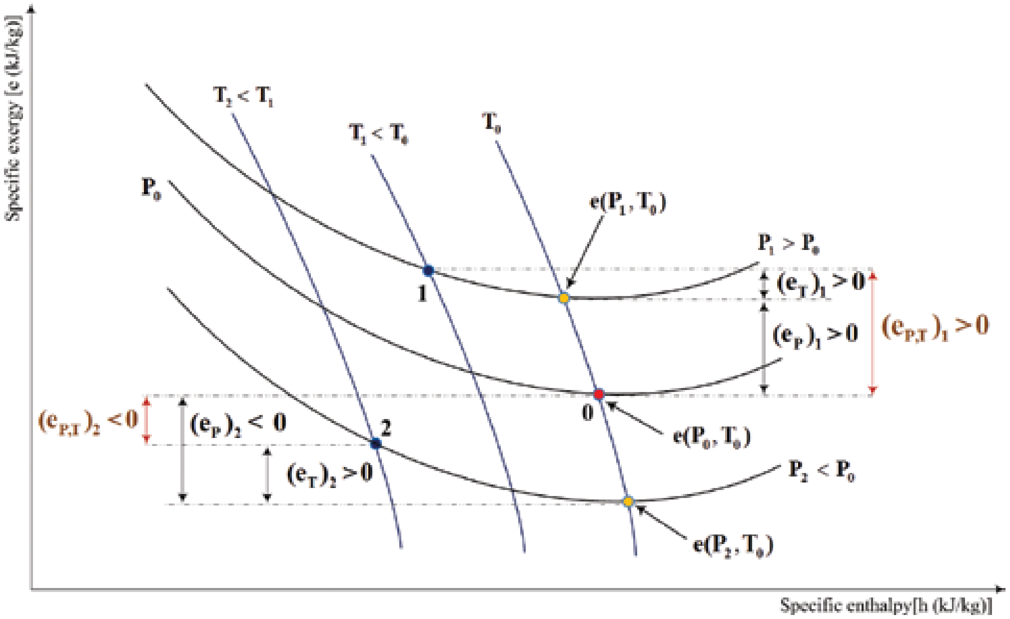

Figure 2. Thermal e_T and mechanical e_P exergy components on an exergy-enthalpy diagram.

Among them, three exergy efficiency definitions may be distinguished: input-output efficiency, products-fuel efficiency, and efficiency that accounts for the transiting exergy.

The input-output efficiency $\eta_{\text{in-out}}$, first proposed by Grassmann [2], is computed according to Eq. (6):

$$\eta_{\text{in-out}} = \frac{\dot{E}_{\text{out}}}{\dot{E}_{\text{in}}} \tag{6}$$

The shortcomings of this definition, particularly for its application to sub-ambient problems, are well documented [3–9]. The main one is the fact that often $\eta_{\text{in-out}}$ does not evaluate the degree to which the technical purpose of a process is realized; the subject will be illustrated in Section 3. The products-fuel efficiency $\eta_{\text{pr-f}}$ proposed by Tsatsaronis [10] and Bejan et al. [6] in the context of expansion and compression processes is computed as:

$$\eta_{\text{pr-f}} = \frac{\text{Exergy of Products}}{\text{Exergy of Fuel}} \tag{7}$$

Under the terms "products" and "fuel" the authors meant either the differences in exergies of the streams at the inlet and outlet of a process, or the exergies of streams themselves. For example, while evaluating the efficiency of an adiabatic compression operating above ambient conditions, the "fuel" is the supplied work, and the "product" is the increment of thermo-mechanical exergy. The problem with this approach is that it is possible to obtain different values of $\eta_{\text{pr-f}}$ of the sub-ambient expansion and compression processes due to the fact that different things can be understood under the notions "products" and "fuel". It should be also mentioned that some authors used a different terminology to express the numerator and denominator of Eq. (7). For example, Kotas [4] used "desired output" vs. "necessary input"; Szargut et al. [5] used "exergy of useful products" vs. "feeding exergy".

Brodyansky et al. [3] proposed a definition of efficiency based on the subtraction of the exergy that has not undergone transformation within an analyzed process. The latter was named "transiting exergy", $\dot{E}_{\text{tr}}$, and the exergy efficiency is defined as:

$$\eta_{\text{tr}} = \frac{\dot{E}_{\text{out}} - \dot{E}_{\text{tr}}}{\dot{E}_{\text{in}} - \dot{E}_{\text{tr}}} = \frac{\Delta\dot{E}}{\nabla\dot{E}} \tag{8}$$

where $\Delta\dot{E}$ and $\nabla\dot{E}$ are the exergy produced and exergy consumed in the process. It is clear that the difference between the denominator and the numerator in Eq. (8) equals the exergy losses within the process. It will be illustrated that the unambiguous definition of $\dot{E}_{\text{tr}}$ paves the way for the uniquely determined thermodynamic metrics $\Delta\dot{E}$ and $\nabla\dot{E}$ in the case of thermo-mechanical exergy transformation for sub-ambient processes. The evaluation of η_{tr} to assess the rate of exergy transfer of the mechanical exergy component to the thermal exergy component for these processes will be based on these metrics.

3. Transiting thermo-mechanical exergy and its link to the thermal and mechanical components

Following the equations proposed by Brodyansky et al. [3], the specific transiting thermo-mechanical exergy e_{tr} of an analyzed system is defined as the minimum exergy value that can be assigned to a material stream, considering the pressure P and temperature T at the inlet and outlet, as well as the ambient temperature T_0. With this definition, there are three possible combinations of P_{in}, T_{in}, P_{out}, T_{out} and T_0 that determine the value of e_{tr}:

$$\text{If } (T_{in} > T_0 \text{ and } T_{out} > T_0): \ \dot{E}_{tr} = \dot{m}.e_{tr}(P_{min}, \mathbf{T_{min}}) \tag{9a}$$

$$\text{If } (T_{in} < T_0 \text{ and } T_{out} < T_0): \ \dot{E}_{tr} = \dot{m} \cdot e_{tr}(P_{min}, \mathbf{T_{max}}) \tag{9b}$$

$$\text{If } (T_{in} > T_0 \text{ and } T_{out} < T_0) \text{OR} (T_{in} < T_0 \text{ and } T_{out} > T_0) \ : \ \dot{E}_{tr} = \dot{m} \cdot e_{tr}(P_{min}, \mathbf{T_0}) \tag{9c}$$

Inspection of these equations shows that for all three cases e_{tr} is determined by using the lowest pressure P_{min} among the inlet and outlet values. The situation is different for temperature, where the minimum exergy value is determined using the lowest temperature T_{min} for processes above ambient, the highest temperature T_{max} for sub-ambient processes, and by using T_0 for the case of processes operating across ambient temperature. In order to understand the physical meaning of the transiting exergy, let us analyze the throttling process of a real gas taking place under these three different temperature conditions.

3.1. Adiabatic throttling process

The case of the throttling process operating above T_0 is presented on an e-h diagram (see **Figure 3a**). According to Eq. (9a), the value of e_{tr} is:

$$e_{tr} = e(P_{out}, T_{out}) \tag{10}$$

This value coincides with the value e_2 as illustrated in **Figure 3a**. The specific exergy losses (d) are also presented on the diagram. Following Eq. (8), the values $\Delta\dot{E}$ and $\nabla\dot{E}$ are:

$$\Delta\dot{E} = \dot{m} \cdot (e_{out} - e_{tr}) = 0 \tag{11}$$

$$\nabla\dot{E} = \dot{m} \cdot (e_{in} - e_{tr}) = \dot{m} \cdot d \tag{12}$$

where $\dot{m}$ is the gas mass flow rate.

As a result, the efficiency $\eta_{tr} = 0$, meaning that the exergy consumed is completely lost during the process and there is no produced exergy. It should be mentioned that the input-output efficiency calculated according to Eq. (6) has a negative value in this particular case and has no physical meaning. This is due to the fact that $\dot{E}_{out} < 0$, because the throttling ended at the vacuum conditions. For this particular case the products-fuel efficiency according to Eq. (7) gives the same value as η_{tr}.

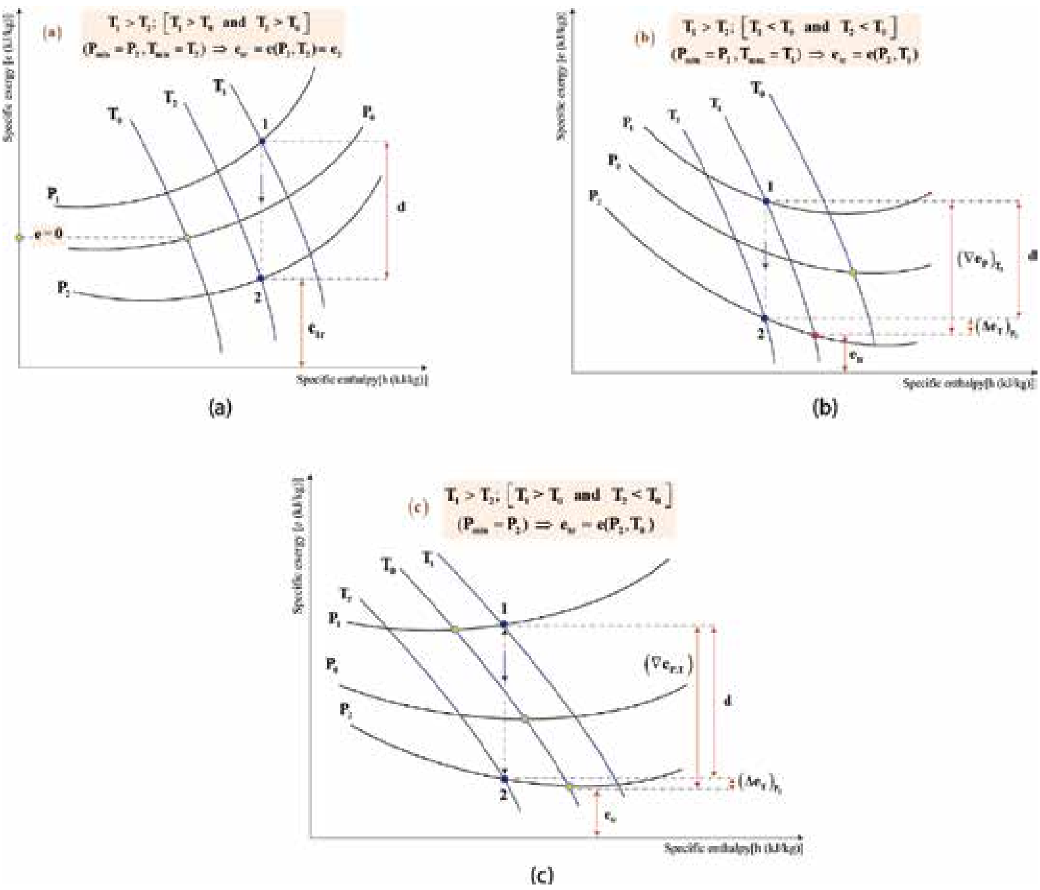

Figure 3. Transiting thermo-mechanical exergy presentation for a throttling process of a real gas operating above (a), below (b), and across (c) ambient temperature (T_0).

Now, let us analyze the case of throttling at sub-ambient conditions presented in **Figure 3b**. According to Eq. (9b):

$$e_{tr} = e(P_{out}, T_{in}) \tag{13}$$

Thus $\Delta\dot{E}$ and $\nabla\dot{E}$ are calculated as:

$$\Delta\dot{E} = \dot{m}\cdot(e_{out} - e_{tr}) = \dot{m}\cdot[e(P_{out}, T_{out}) - e(P_{out}, T_{in})] = \dot{m}\cdot(\Delta e_T)_{P_{out}} \tag{14}$$

$$\nabla\dot{E} = \dot{m}\cdot(e_{in} - e_{tr}) = \dot{m}\cdot[e(P_{in}, T_{in}) - e(P_{out}, T_{in})] = \dot{m}\cdot(\nabla e_P)_{T_{in}} \tag{15}$$

The term $(\Delta e_T)_{Pout}$ in Eq. (14) is the increase of the specific thermal exergy due to an isobaric temperature drop under **sub-ambient** conditions at constant pressure P_{out}. The term $(\nabla e_P)_{Tin}$ in Eq. (15) is the decrease of the specific mechanical exergy due to an isothermal pressure drop at constant temperature T_{in}. Finally, the case presented in **Figure 3c** illustrates a throttling process started above ambient and ended at sub-ambient conditions. According to Eq. (9c):

$$e_{tr} = e(P_{out}, T_0) \tag{16}$$

The values $\Delta\dot{E}$ and $\nabla\dot{E}$ are calculated as:

$$\Delta\dot{E} = \dot{m} \cdot (e_{out} - e_{tr}) = \dot{m} \cdot [e(P_{out}, T_{out}) - e(P_{out}, T_0)] = \dot{m} \cdot (\Delta e_T)_{P_{out}} \tag{17}$$

$$\nabla\dot{E} = \dot{m} \cdot (e_{in} - e_{tr}) = \dot{m} \cdot [e(P_{in}, T_{in}) - e(P_{out}, T_0)] = \dot{m} \cdot (\nabla e_{P,T}) \tag{18}$$

Again, the input-output efficiency is not suitable for the evaluation of the processes presented in **Figure 3b** and **c**, given that the outlet exergy $e_2 = e(P_{out}, T_{out})$ is negative. Another difficulty is linked to the application of the products-fuel efficiency for these cases. The exergy transfer of the throttling process at sub-ambient conditions consists in the partial transformation of mechanical exergy ("fuel") into thermal exergy ("product"). The problem stems from the fact that there are multiple possibilities to define "fuel" and "product" in this case; as a result multiple values of $\eta_{pr\text{-}f}$ may be formulated, leading to the ambiguity in the products-fuel efficiency application. Indeed, the different increments of thermal exergy may be considered as a "product" for the case in **Figure 3b**, for example, the increase in thermal exergy following the isobar P_1 or the isobar P_2. In the same way, different decrements of mechanical exergy may be considered as a "fuel" in the same figure, for example, the decrease of mechanical exergy following the isotherms T_1 or T_2.

Contrary to "products-fuel", the transiting exergy approach does not attempt to individually compute the thermal and mechanical exergy component variations. It relies, rather, on the unaffected part of the thermo-mechanical exergy entering and leaving the system.

As illustrated in **Figure 3a** and **c**, the transiting exergy may be considered as the introduction of a new reference state to evaluate exergy consumed and produced. Instead of the reference point e = 0 (the intersection of the isobar P_0 and the isotherm T_0), the new reference point is presented by e_{tr}: the intersection of the isobar P_2 and the isotherm T_2 for the case 3a; of the isobar P_2 and the isotherm T_1 for the case 3b; and of the isobar P_2 and the isotherm T_0 for the case 3c. Finally, the transiting exergy approach provides the foundation for the non-ambiguous definition of the terms $\Delta\dot{E}$ and $\nabla\dot{E}$, and thus of η_{tr}.

Example 1

The initial parameters of air at the inlet of a throttling valve are: $\dot{m}$ = 1 kg/s, P_1 = 3 MPa, T_1 = 140 K. The ambient temperature T_0 = 283 K. Calculate the variation of $\dot{E}_{tr}$, $\Delta\dot{E}$ and $\nabla\dot{E}$ and η_{tr} as a function of the outlet pressure P_2 in the range 0.1–1 MPa.

Solution

The outlet temperature of the air is calculated by using the software Engineering Equation Solver (EES) [11]. Given that the expansion of air takes place at sub-ambient conditions, Eqs. (13)–(15) are used to evaluate $\dot{E}_{tr}$, $\Delta\dot{E}$ and $\nabla\dot{E}$. The results are presented in **Table 1**. One observation is obvious, that the rise in exergy losses as well as the decrease in η_{tr} go along with

P_2 (MPa)	T_2 (K)	$\nabla\dot{E}$ (kW)	$\Delta\dot{E}$ (kW)	$\dot{D}$ (kW)	$\dot{E}_{tr}$ (kW)	η_{tr} (%)
1.0	118.6	101.8	30.8	71.0	245.9	30.3
0.9	117.3	110.8	32.4	78.4	236.9	29.2
0.7	114.7	132.0	35.6	96.4	215.7	26.9
0.5	111.9	160.1	38.8	121.3	187.6	24.2
0.3	109.1	202.3	42.1	160.2	145.4	20.8
0.1	106.0	292.3	45.5	246.8	55.5	15.6

Table 1. Variation in temperature and exergy metrics with the outlet pressure for a throttling process of air.

the decreasing outlet pressure P_2. Less obvious is that the exergy produced $\Delta\dot{E}$ rises with decreasing P_2, reflecting the production of a more important cooling effect. It can also be noticed that the transiting exergy $\dot{E}_{tr}$ decreases with decreasing outlet pressure P_2.

Example 2

The expansion valve of a refrigeration mechanical vapor compression cycle is supplied with the subcooled working fluid R152a at the rate $\dot{m}$ = 0.15 kg/s at P_1 = 615.1 kPa. The fluid is expanded to a pressure of P_2 = 142.9 kPa. The ambient temperature T_0 = 278 K. Calculate the variation of $\dot{E}_{tr}$, $\Delta\dot{E}$ and $\nabla\dot{E}$ and η_{tr} as a function of the subcooling ΔT_{subC} in the range 275–281 K.

Solution

A vapor compression cycle is presented on a Ts-diagram in **Figure 4**. The subcooling process is represented by the line 3f-3. Given that the expansion of R152a takes place across ambient temperature, Eqs. (16)–(18) are used to evaluate $\dot{E}_{tr}$, $\Delta\dot{E}$ and $\nabla\dot{E}$. The results are shown in **Table 2**.

The transiting exergy does not change with the subcooling, because it is the function of constant parameters T_0 and P_2, meanwhile the exergy produced increases and exergy consumed decreases. The new result is that η_{tr} is rising with the subcooling. It should be mentioned that increasing the amount of subcooling is well documented as a way to increase the COP (coefficient of performance) of vapor compression cycles [4]. Thus, the rise in η_{tr} of an expansion device guarantees the COP improvement of the overall cycle, a conclusion that may lead to practical recommendations for optimization of refrigeration cycles.

3.2. Expansion in low temperature systems with work production and heat transfer

The primary purpose of expansion processes in the sub-ambient region is the production of cooling effect. The power that may be produced can be considered as a useful by-product. This type of expansion takes place in cryo-expanders. There are two types of these devices: adiabatic and non-adiabatic gas expansion machines. The energy and exergy balances around a non-adiabatic expander are presented in **Figure 5**. It should be emphasized that the directions

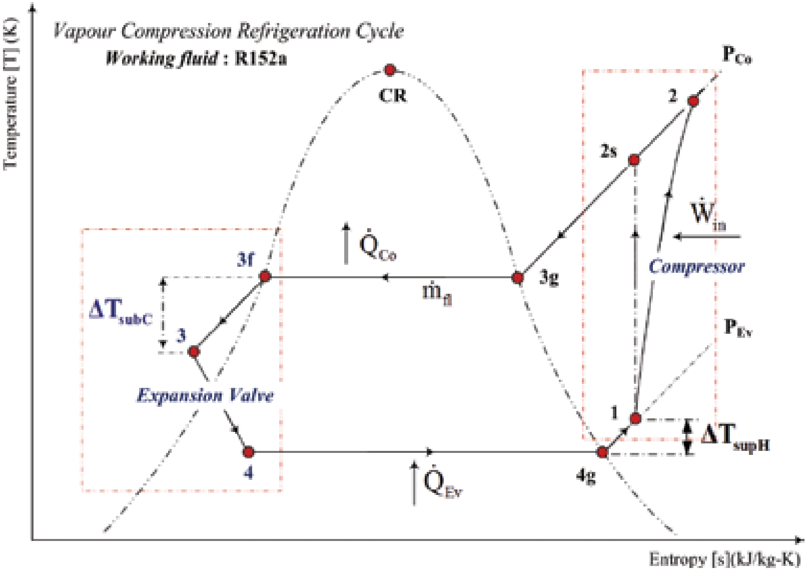

Figure 4. A vapor compression cycle presentation on a Ts-diagram.

ΔT_{subC} (K)	$\nabla \dot{E}$ (kW)	$\Delta \dot{E}$ (kW)	$\dot{D}$ (kW)	$\dot{E}_{tr}$ (kW)	η_{tr} (%)
275	4.083	3.208	0.875	1.744	78.6
276	4.066	3.230	0.836	1.744	79.4
278	4.034	3.274	0.760	1.744	81.2
279	4.020	3.295	0.725	1.744	82.0
281	3.994	3.339	0.655	1.744	83.6

Table 2. Variation in exergy metrics with subcooling for the expansion process of R152a.

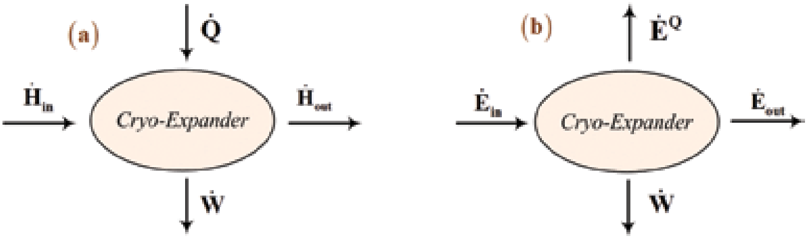

Figure 5. Energy (a) and exergy (b) balances around a non-adiabatic cryo-expander.

of heat flow $\dot{Q}$ and exergy $\dot{E}^Q$ are opposite. This is due to the fact that heat transfer from a cooled object to the expanding fluid occurs at $T < T_0$. As a result $\dot{E}^Q$ calculated according to Eq. (1) is presented as the outlet flow in **Figure 5b**.

The process of gas expansion in a non-adiabatic cryo-expander is presented on an e-h diagram (see **Figure 6**). Similar to the case of adiabatic throttling (**Figure 3b**), the transiting exergy in the gas flow is defined according to Eq. (9b). As a result, the exergy efficiency is calculated as:

$$\eta_{tr} = \frac{\dot{m}\cdot(\Delta e_T)_{P_{out}} + \dot{Q}\cdot\Theta + \dot{W}_T}{\dot{m}\cdot(\nabla e_P)_{T_{in}}} \tag{19}$$

In the case of an adiabatic cryo-expander η_{tr} is calculated according to Eq. (19), but with the term $\dot{Q}.\Theta_{in}$ equals to zero.

Example 3

An adiabatic turbine ($\eta_T = 0.80$) is supplied with air at the rate $\dot{m} = 1$ kg/s at $P_1 = 6$ MPa, $T_1 = 320$ K. The ambient temperature $T_0 = 283$ K. Calculate the variation of $\dot{E}_{tr}$, $\Delta\dot{E}$ and $\nabla\dot{E}$ and η_{tr} as a function of the outlet pressure P_2 in the range 0.1–3 MPa.

Solution

Given that the expansion of air takes place across ambient temperature, Eqs. (16)–(18) are used to evaluate $\dot{E}_{tr}$, $\Delta\dot{E}$ and $\nabla\dot{E}$. η_{tr} is calculated according to Eq. (19), but with the term $\dot{Q}.\Theta_{in}$ equals to zero. The results are shown in **Table 3**. It is illustrated that $\dot{E}_{tr}$ decreases with P_2 reduction, and as a result $\Delta\dot{E}$ and $\nabla\dot{E}$ and $\dot{W}$ rise, but the increase in $\Delta\dot{E}$ and $\dot{W}$ is offset by the greater increase in $\nabla\dot{E}$ causing η_{tr} to decrease. The negative value of $\dot{E}_{tr}$ in the second last row to the right in **Table 3**, is because the stream at state 2 is under vacuum conditions. It should be

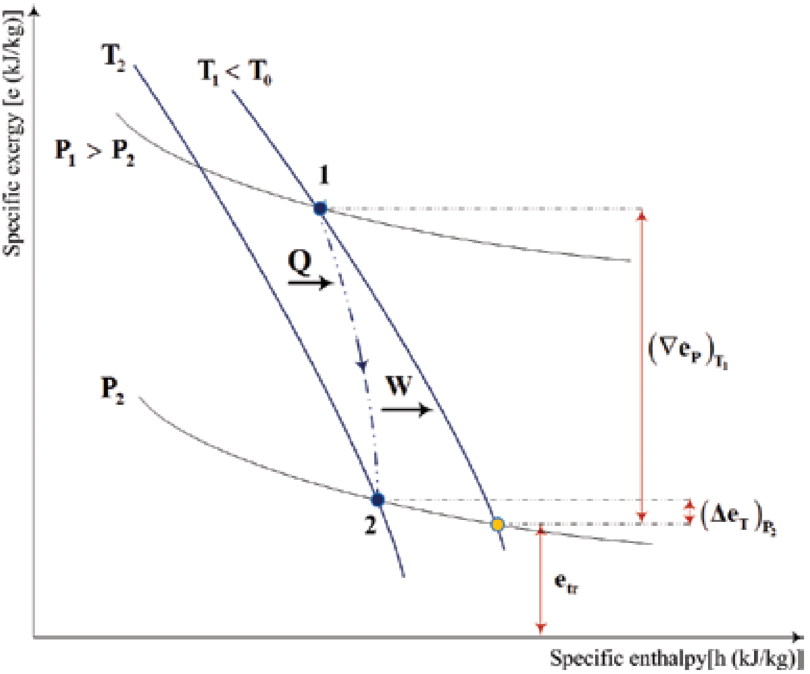

Figure 6. Gas expansion in a non-adiabatic cryo-expander on an exergy-enthalpy diagram.

P_2 (MPa)	T_2 (K)	$\nabla\dot{E}$ (kW)	$\Delta\dot{E}$ (kW)	$\dot{W}_T$ (kW)	$\dot{D}$ (kW)	$\dot{E}_{tr}$ (kW)	η_{tr} (kW)
3.00	271.8	57.9	0.2	45.6	12.1	274.2	79.1
2.55	263.8	68.3	0.7	53.0	14.6	263.9	78.7
2.50	255.1	80.1	1.5	61.2	17.4	252.0	78.2
1.85	245.4	94.1	2.9	70.3	21.0	238.0	77.7
1.50	234.3	111.1	4.9	80.7	25.5	221.1	77.1
1.15	221.2	132.6	8.2	93.1	31.3	199.6	76.4
0.50	204.9	162.0	13.6	108.4	40.0	170.1	75.3
0.45	182.4	208.9	24.1	129.7	55.1	123.2	73.6
0.10	138.9	333.2	57.7	171.6	103.9	−1.05	68.8

Table 3. Variation in exergy metrics with the outlet pressure for a turbine expansion process.

emphasized that the increase in the $\Delta\dot{E}$ metric reflects the deeper refrigeration of air with increasing pressure drop in the turbine.

3.3. Expansion in a vortex tube

Figure 7a illustrates a counter flow vortex tube [12]. High pressure gas enters the tube through a tangential nozzle (point 1). Colder low-pressure gas leaves via an orifice near the centerline adjacent to the plane of the nozzle (point 2), and warmer low-pressure gas leaves near the periphery at the end of the tube opposite to the nozzle (point 3). The vortex tube requires no work or heat interaction with the surroundings to operate. The cold mass fraction is μ; the hot gas mass fraction is (1 − μ). The exergy balance around the vortex tube is:

$$e_1 = \mu \cdot e_2 + (1 - \mu) \cdot e_3 + d \tag{20}$$

The expansion processes taking place within a vortex tube are presented on an e-h diagram (**Figure 7b**). The cold stream expands across T_0, the hot expands at $T > T_0$. By applying Eqs. (9a) and (9c) the transiting exergies may be determined for each mass stream, cold (1–2) and hot (1–3).

$$(e_{tr})_{cold} = e(P_2, T_0) \tag{21}$$

$$(e_{tr})_{hot} = e(P_3, T_1) \tag{22}$$

As a result, the exergy produced and consumed within the cold and hot streams are:

$$\begin{aligned} \Delta\dot{E}_C &= \dot{m} \cdot [(\mu) \cdot (e(P_2, T_2) - e(P_2, T_0))] = \dot{m} \cdot (\mu) \cdot (\Delta e_T)_{P_2} \\ \Delta\dot{E}_H &= \dot{m} \cdot [(1 - \mu) \cdot (e(P_3, T_3) - e(P_3, T_1))] = \dot{m} \cdot (1 - \mu) \cdot (\Delta e_T)_{P_3} \end{aligned} \tag{23}$$

$$\begin{aligned} \nabla\dot{E}_C &= \dot{m} \cdot [(\mu) \cdot (e(P_1, T_1) - e(P_2, T_0))] = \dot{m} \cdot (\mu) \cdot (\nabla e_{P,T}) \\ \nabla\dot{E}_H &= \dot{m} \cdot [(1 - \mu) \cdot (e(P_1, T_1) - e(P_3, T_1))] = \dot{m} \cdot (1 - \mu) \cdot (\nabla e_P)_{T_1} \end{aligned} \tag{24}$$

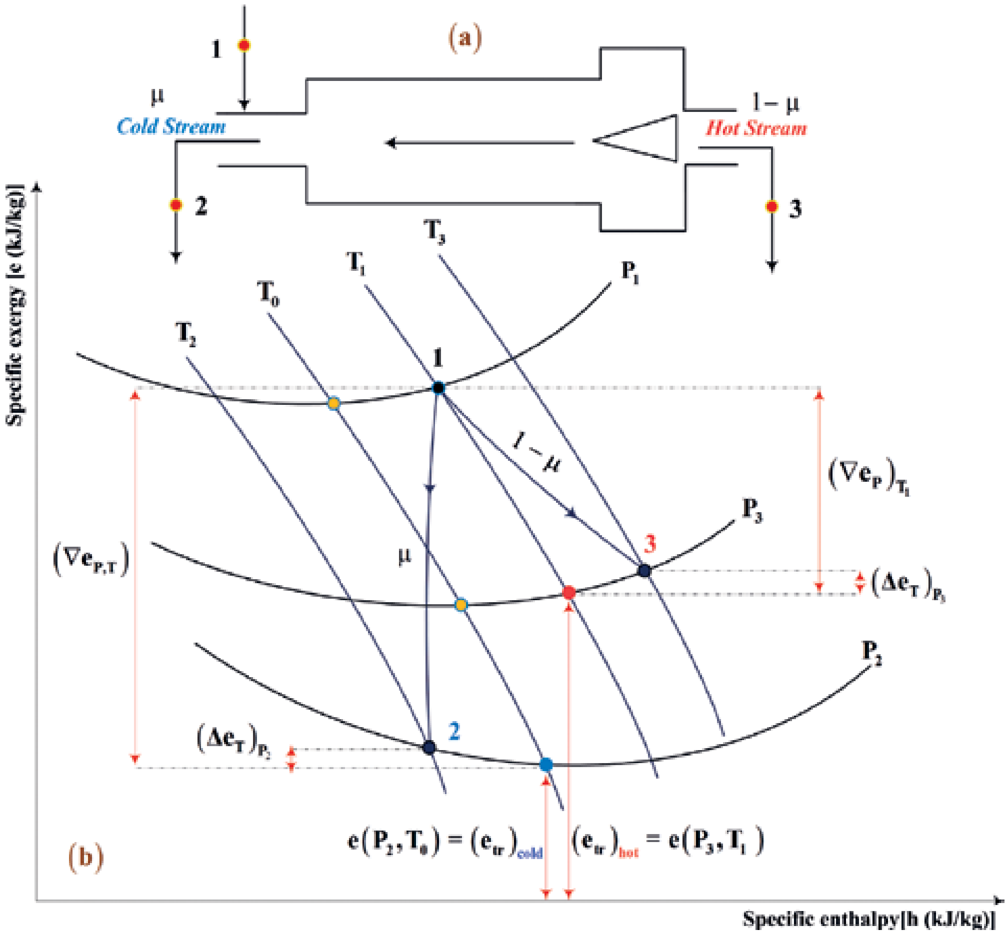

Figure 7. A vortex tube (a) and the presentation of the expansion process on an exergy-enthalpy diagram (b).

Thus $\Delta\dot{E}_C$ and $\Delta\dot{E}_H$ represent the increase in the thermal exergy component due to the cooling of the cold stream and the heating for the hot stream, under conditions of the outlet pressures for each stream. $\nabla\dot{E}_C$ represents the decrease in thermo-mechanical exergy of the cold stream due to the partial thermal exergy destruction because of the temperature drop from T_1 to T_0, and the decrease of mechanical exergy because of pressure drop from P_1 to P_3. $\nabla\dot{E}_H$ is the decrease of mechanical exergy of the hot stream at conditions of constant inlet temperature. The ratio $(\Delta\dot{E}_C + \Delta\dot{E}_H) / (\nabla\dot{E}_C + \nabla\dot{E}_H)$ gives the value of η_{tr}.

Example 4

An adiabatic vortex tube is supplied with air as ideal gas at the rate $\dot{m}$ = 1 kg/s and at P_1 = 0.8 MPa, T_1 = 308 K. The air expands at the cold end to pressure P_2 = 0.1 MPa and at the hot end to the pressure P_3 = 0.15 MPa. The ambient temperature T_0 = 298 K. Calculate the variation of $\dot{E}_{tr}$, $\Delta\dot{E}$ and $\nabla\dot{E}$ and η_{tr} as a function of the cold mass fraction μ in the range 0.2–0.9.

Solution

The results are shown in **Table 4**. It is illustrated that $\dot{E}_{tr,}$ H decreases with the cold mass fraction increase. The $\dot{E}_{tr,C}$ is zero, because it is defined by ambient conditions $P_2 = P_0$ and $T_2 = T_0$. As a result, for the cold stream $\Delta\dot{E}_C$ decreases but $\nabla\dot{E}_C$ increases strongly with μ. An opposite effect is observed for the hot stream, where $\Delta\dot{E}_H$ increases and $\nabla\dot{E}_H$ decreases. As a result, η_{tr} increases, despite the rise in the exergy losses with the increasing cold mass fraction. This can be explained by the fact that the rise in exergy produced in the hot stream surpasses the increase in exergy losses. The exergy efficiency of the vortex tube is relatively low.

3.4. Compression across ambient temperature

In most refrigeration plants and heat pumps compression starts at $T < T_0$ and ends at $T > T_0$. The process is presented on an e-h diagram (see **Figure 8**). According to Eq. (9c), transiting exergy is:

$$e_{tr} = e(P_1, T_0) \tag{25}$$

The produced and consumed exergies are:

$$\Delta\dot{E} = \dot{m} \cdot [e(P_2, T_2) - e(P_1, T_0)] = \dot{m} \cdot (\Delta e_{P,T}) \tag{26}$$

$$\left(\nabla\dot{E} + \dot{W}_C\right) = \dot{m} \cdot [e(P_1, T_1) - e(P_1, T_0)] + \dot{W}_C = \dot{m} \cdot (\nabla e_T)_{P_1} + \dot{W}_C \tag{27}$$

$\Delta\dot{E}$ represents the increase of thermo-mechanical exergy due to the rise in pressure from P to P_2 and the rise in temperature from T_0 to T_2. $\nabla\dot{E}$ represents the destruction of thermal exergy due to the rise in temperature from T_1 to T_0 under conditions of constant pressure P_1, plus the consumed power $\dot{W}_C$. The ratio $\Delta\dot{E}/(\nabla\dot{E} + \dot{W}_C)$ gives the value of exergy efficiency η_{tr}.

Example 5

An adiabatic compressor of a refrigeration plant is supplied with the working fluid R152a at the rate $\dot{m} = 1$ kg/s at $P_1 = 142.9$ kPa and $T_1 = 263$ K (superheated). The fluid is compressed to a pressure of $P_2 = 615.1$ kPa. The ambient temperature $T_0 = 298$ K. Calculate the variation of $\dot{E}_{tr}$, $\Delta\dot{E}$ and $\nabla\dot{E}$ and η_{tr} as a function of the isentropic efficiency η_C in the range 0.75–0.90.

μ (–)	T_2 (K)	T_3 (K)	$\nabla\dot{E}_C$ (kW)	$\Delta\dot{E}_C$ (kW)	$\dot{E}_{tr,C}$ (kW)	$\nabla\dot{E}_H$ (kW)	$\Delta\dot{E}_H$ (kW)	$\dot{E}_{tr,H}$ (kW)	$\dot{D}$ (kW)	η_{tr} (%)
0.35	268.0	329.5	61.9	0.6	0.0	93.1	0.9	21.9	153.5	0.97
0.60	273.0	360.4	106.2	0.7	0.0	57.3	2.3	13.5	160.5	1.83
0.75	278.0	397.6	132.7	0.5	0.0	35.8	3.4	8.4	164.6	2.32

Table 4. Variation in exergy metrics with the cold mass fraction for a vortex tube expansion process.

Solution

The results are shown in **Table 5**. The transiting exergy does not change with the isentropic efficiency η_C, because is a function of constant parameters T_0 and P_1. The exergy consumed does not change either. The produced exergy decreases. This drop in $\Delta\dot{E}$ is explained by the reduction in "compression reheat". The decrease in $\Delta\dot{E}$ is offset by the greater decrease in $\dot{W}_C$, and as a result η_{tr} increases.

3.5. Compression and expansion in a one phase ejector

A combination of the processes of vapor expansion and compression takes place within a one-phase ejector presented in **Figure 9a**. A primary (pr) stream at high pressure P_1 and temperature

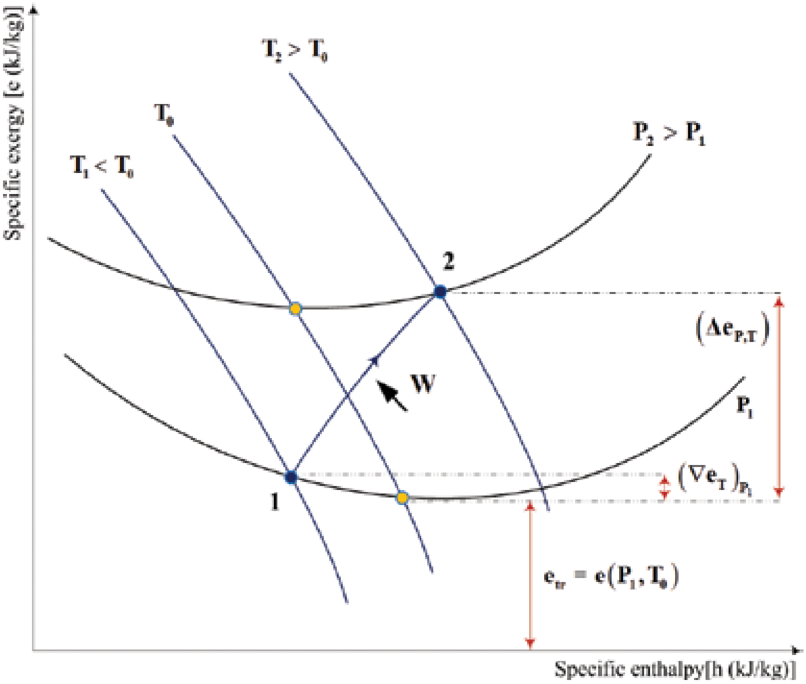

Figure 8. Compression process across ambient temperature (T_0) on an exergy-enthalpy diagram.

η_C (–)	$\dot{W}_C$ (kW)	$\nabla\dot{E}$ (kW)	$\Delta\dot{E}$ (kW)	$\dot{D}$ (kW)	$\dot{E}_{tr}$ (kW)	η_{tr} (kW)
0.75	66.0	2.3	53.3	15.0	12.6	78.0
0.80	61.9	2.3	52.9	11.3	12.6	82.4
0.85	58.3	2.3	52.6	8.0	12.6	86.8
0.90	55.0	2.3	52.3	5.0	12.6	91.3

Table 5. Variation in exergy metrics with the isentropic efficiency for a compression process.

T_1 expands and entrains a secondary stream (s) at low pressure P_2 and temperature $T_2 < T_0$. The ratio $\dot{m}_s/\dot{m}_{pr}$ gives the value of the entrainment ratio (ω) of the ejector. The mixed stream with the parameters $P_2 < P_3 < P_1$ and $T_2 < T_3 < T_1$ leaves the ejector. The exergy balance around the ejector is:

$$\left(\frac{1}{1+\omega}\right) \cdot e_1 + \left(\frac{\omega}{1+\omega}\right) \cdot e_2 = e_3 + d \tag{28}$$

The processes of expansion of the primary stream and compression of the secondary stream are presented on an e-h diagram (**Figure 9b**). The secondary stream is compressed across T_0, meaning that Eq. (9c) is applied to calculate $(e_{tr})_s$. As a result, the transiting exergy for secondary and primary streams are:

$$(e_{tr})_s = e(P_2, T_0) \tag{29}$$

$$(e_{tr})_{pr} = e(P_3, T_3) \tag{30}$$

This means that the exergies produced and consumed may be computed as:

$$\Delta\dot{E}_s = \dot{m}_s \cdot [e(P_3, T_3) - e(P_2, T_0)] = \dot{m}_s \cdot (\Delta e_{P,T})_s \tag{31}$$

$$\begin{aligned} \nabla\dot{E}_s &= \dot{m}_s \cdot [e(P_2, T_2) - e(P_2, T_0)] = \dot{m}_s \cdot \left((\nabla e_T)_{P_2}\right)_s \\ \nabla\dot{E}_{pr} &= \dot{m}_{pr} \cdot [e(P_1, T_1) - e(P_3, T_3)] = \dot{m}_{pr} \cdot (\nabla e_{P,T})_{pr} \end{aligned} \tag{32}$$

$\Delta\dot{E}_s$ is the increase of thermo-mechanical exergy of the secondary stream due to the compression from P_2 to P_3 and the rise in temperature from T_0 to T_3. The exergy consumed $\nabla\dot{E}_s$ within the secondary stream represents the decrease of thermal exergy component because of the temperature rise from T_2 to T_0 (the partial cold destruction). The exergy consumed within the primary stream $\nabla\dot{E}_{pr}$ is the decrease of thermo-mechanical exergy The ratio $\Delta\dot{E}_s/(\nabla\dot{E}_s + \nabla\dot{E}_{pr})$ gives the value of exergy efficiency η_{tr}. The detailed analysis of efficiencies for different parts of an ejector is given in [13].

Example 6

An ejector of a refrigeration plant is supplied with the working fluid R141b. The parameters of the secondary stream are: P_2 = 22.3 kPa, T_2 = 268 K. The pressure of the mixed stream is P_3 = 91 kPa. The ambient temperature T_0 = 289 K. Calculate the variation of $(\dot{E}_{tr})_{pr}$, $(\dot{E}_{tr})_s$, $\Delta\dot{E}$ and $\nabla\dot{E}$ and η_{tr} as a function of the entrainment ratio $\omega = \dot{m}_s/\dot{m}_{pr}$ in the range 0.15–0.25.

Solution

The calculation results are shown in **Table 6**. The transiting exergy in the secondary flow is negative because the parameters P_2 and T_0 define the state of the flow under vacuum conditions. The exergy produced and exergy consumed increase with the entrainment factor. The increase in $\Delta\dot{E}_s$ offsets the increase in $(\nabla\dot{E}_s + \nabla\dot{E}_{pr})$, and as a result η_{tr} increases.

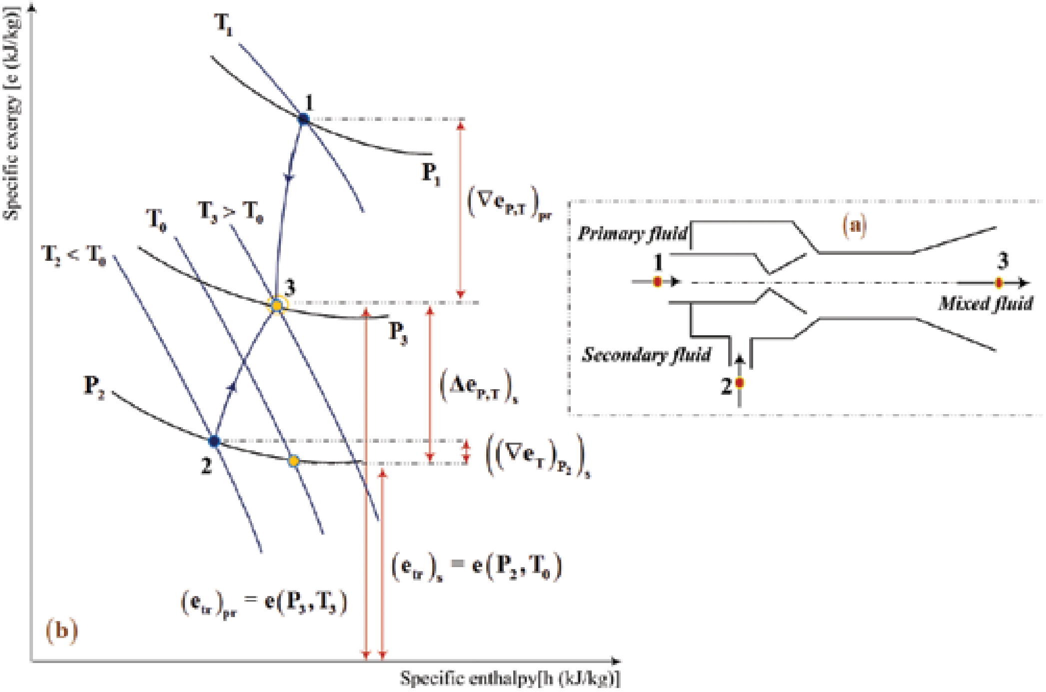

Figure 9. One phase ejector (a) and presentation of expansion and the compression processes (b) on an exergy-enthalpy diagram.

ω (–)	$\nabla\dot{E}_{pr}$ (kW)	$\nabla\dot{E}_s$ (kW)	$\Delta\dot{E}_s$ (kW)	$\dot{D}$ (kW)	$\dot{E}_{tr,pr}$ (kW)	$\dot{E}_{tr,s}$ (kW)	$\dot{E}_{tr}$ (kW)	η_{tr} (%)	P_1 (kPa)	T_1 (K)
0.15	9.99	0.017	1.189	8.818	4.286	−0.546	3.740	11.9	1000	418
0.17	10.07	0.019	1.334	8.755	4.205	−0.619	3.586	13.2	1000	418
0.20	10.19	0.023	1.547	8.666	4.090	−0.729	3.361	15.2	1000	418
0.23	10.29	0.026	1.754	8.562	3.983	−0.838	3.145	17.0	1000	418
0.25	10.36	0.028	1.890	8.498	3.915	−0.911	3.004	18.2	1000	418

Table 6. Variation in exergy metrics with the entrainment factor for compression-expansion processes in an ejector.

4. Environmental life cycle analysis and exergy efficiency of cooling systems

Life Cycle Analysis (LCA) is an important tool to analyze environmental problems associated with the production, use, and disposal of products or systems [14]. For every product produced within a system the total inflow and outflow of energy and materials are evaluated. The environmental burdens are associated by quantifying the energy and materials used, as well as the wastes released into the environment. The impact of these uses and releases on the environment is assessed. The multidimensional approach of LCA causes some problems when different substances need to be compared and general agreement is required. This problem may be avoided if exergy is used as a common quantity as proposed by Life Cycle Exergy Analysis [15]. The crucial idea behind this method is the distinction between renewable and non-renewable resources. In order to illustrate the method, let us consider three defined time periods within the life cycle of an ejector refrigeration system driven by solar energy [16]. At first, exergy is required during the construction stage to build the plant and put it into operation. During this period the spent exergy is stored in materials, such as metals, glass etc. For the second period, maintenance required for the system's operation takes place. Exergy necessary for this maintenance is evaluated. The third period is the clean-up stage, including the plant demolition and the recycling of materials. Exergy used for the clean-up is assessed. The exergy used for the construction, maintenance, and clean-up is assumed to originate from non-renewable resources and is named indirect exergy, $\dot{E}_{ind}$. When the ejector refrigeration system driven by solar energy is put into operation, it starts to deliver a product (cold in this case) with exergy, $\dot{E}_{pr}$. By considering renewable resources (solar in this case) as free, there will be a net exergy output from the plant until the plant is decommissioned. By considering the total life cycle of the plant the net produced exergy becomes $\dot{E}_{net} = \dot{E}_{pr} - \dot{E}_{ind}$. The higher this value is for the three time periods defined above, the more sustainable the system is, because the input of non-renewable resources will be paid back during the system's lifetime. The rise in exergy efficiency of an ejector calculated according to Eqs. (31) and (32) leads to an increase in efficiency of the solar driven refrigeration system [16]. This in turn means that the net produced exergy $\dot{E}_{net}$ increases too. Thus, the evaluation of η_{tr} of an ejector, as presented in Section 3.5, and its subsequent maximization, may lead to the construction and operation of more sustainable solar driven refrigeration plants.

5. Conclusion

The common feature of expansion processes operating below or across ambient temperature is the partial transformation of the mechanical exergy component into the thermal exergy component. Sub-ambient compression processes are characterized by the transformation of work into the mechanical exergy component and the partial destruction of the thermal exergy component below T_0. In order to evaluate the efficiency of these transformations the calculations of the variation in mechanical and thermal exergy components are required. These calculations may be done in many different ways, for example the variation in e_P depends on the chosen temperature conditions, while the variation in e_T depends on the chosen pressure conditions. This multiplicity in the exergy variation evaluation leads to ambiguity in the exergy efficiency definition. The approach based on the exclusion of the "transiting flow" from thermo-mechanical inlet and outlet exergies of an analyzed process overcomes this difficulty. This improvement is possible because the transiting exergy is uniquely defined by a specific combination of the process intensive parameters, namely the inlet and outlet pressures and temperatures, as well as T_0. The transiting exergy approach allows non-ambiguous evaluation of two thermodynamic metrics: exergy produced and exergy consumed. Their ratio represents the exergy efficiency; the difference between exergy consumed and exergy produced equals the exergy losses within the process. The phenomenological significance of the transiting exergy and the way in which it can be computed for processes below and across T_0 has been illustrated for the cases of an expansion valve, a cryo-expander, a vortex tube, an adiabatic compressor, and a monophasic ejector. The input-output exergy efficiency is not an appropriate criterion for evaluation of these processes.

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Nomenclature

$\dot{D}$	Destroyed exergy, (kW)
d	Specific exergy losses, (kJ/kg)
e	Specific exergy, (kJ/kg)
$\dot{E}$	Exergy, (kW)
h	Specific enthalpy, (kJ/kg)
$\dot{H}$	Enthalpy, (kW)
$\dot{m}$	(Total) Mass flowrate, (kg/s)
P	Pressure, (MPa, kPa)
$\dot{Q}$	Heat rate, (kW)
s	Specific entropy, (kJ/kg K)
T	Temperature, (K, °C)
$\dot{W}$	Mechanical power, (kW)

Greek symbols

η	Efficiency, (%)
∇	Consumption
Δ	Production

μ	Cold mass fraction, $\mu = \dot{m}_C/\dot{m}$
ω	Entrainment ratio

Subscripts

0	Ambient state
1, 2, 3…	States in a process
C	Cold, Compressor
f	Fuel
H	Hot
in	Inlet
ind	Indirect
int	Internal
max	Maximal
min	Minimal
out	Outlet
pr	Primary, Product
S,s	Secondary
subC	Subcooling
tr	Transiting

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New Passive Cooling as a Technique for Hot Arid Climate

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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 ($-0.5 < \text{PMV} < +0.5$). 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/m^2. 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

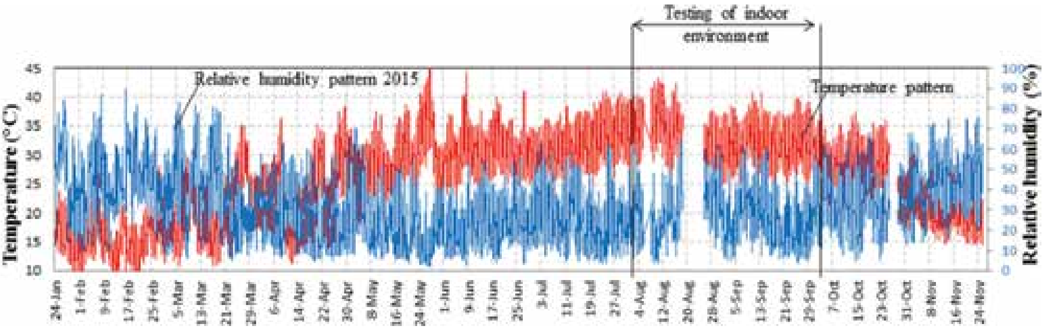

Figure 1. Temperature and humidity pattern of outdoor condition during the year of 2015.

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.

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**.

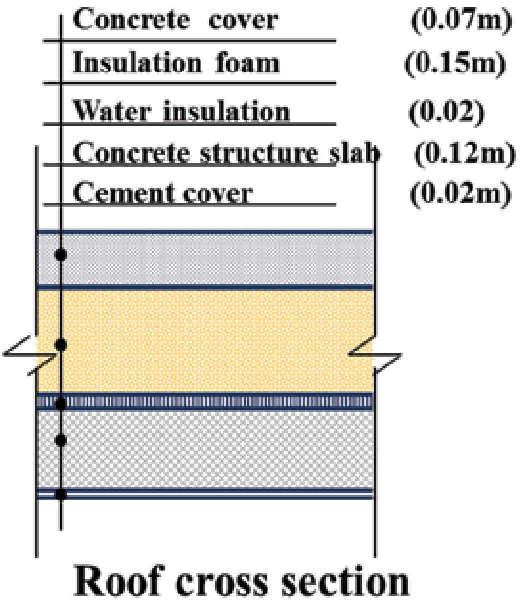

Figure 3. The description of roof layers and their thicknesses.

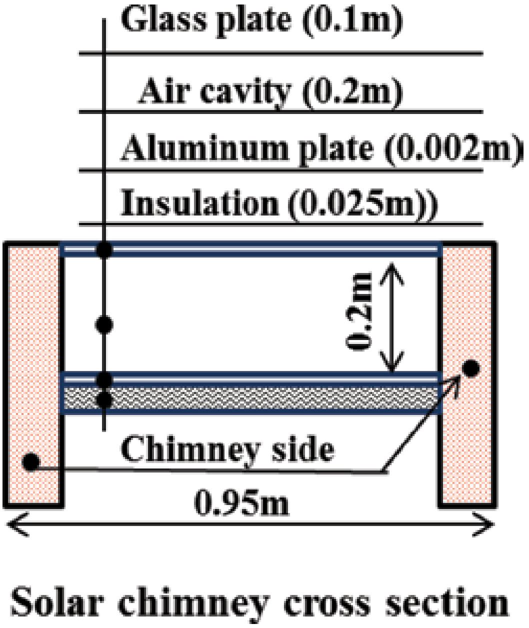

Figure 4. Cross section of the solar chimney cross section.

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].

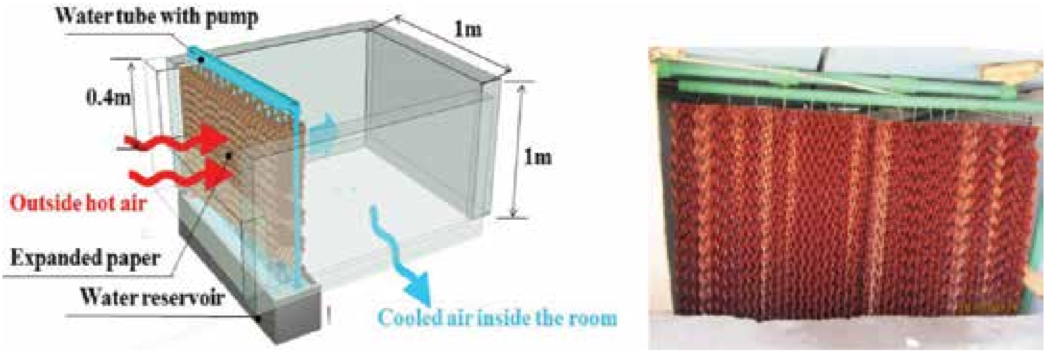

Figure 5. The description of evaporative technique in the wind tower made from expanded paper with water droplet from upper side.

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

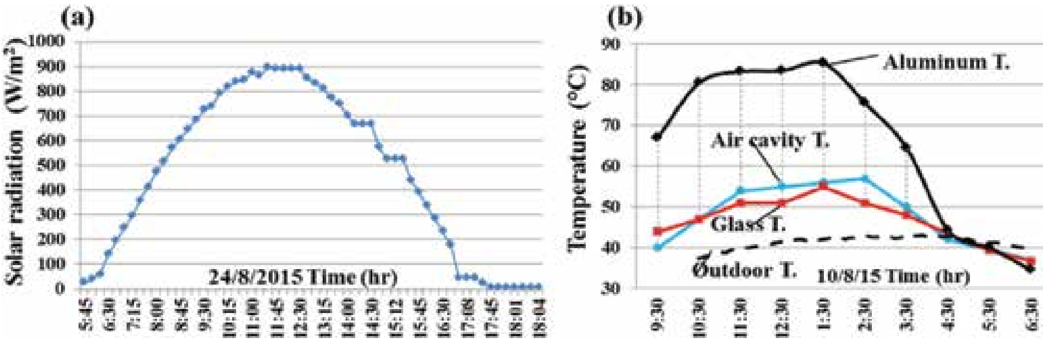

Figure 6. (a) The variation of daily solar radiation over to time. (b) The variation of different temperatures with time.

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.

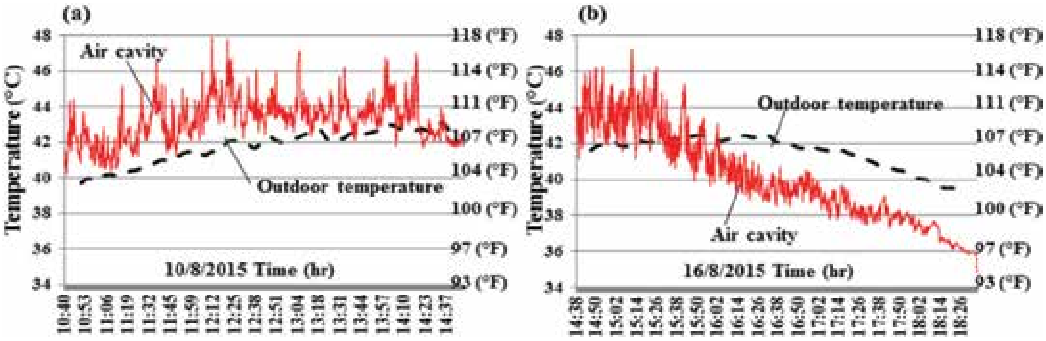

Figure 7. (a) Temperature profile of outlet air inside the chimney cavity from 10:00 am until 14:45 pm. (b) Temperature profile of outlet air inside the chimney cavity from 14:38 am until 18:30 pm.

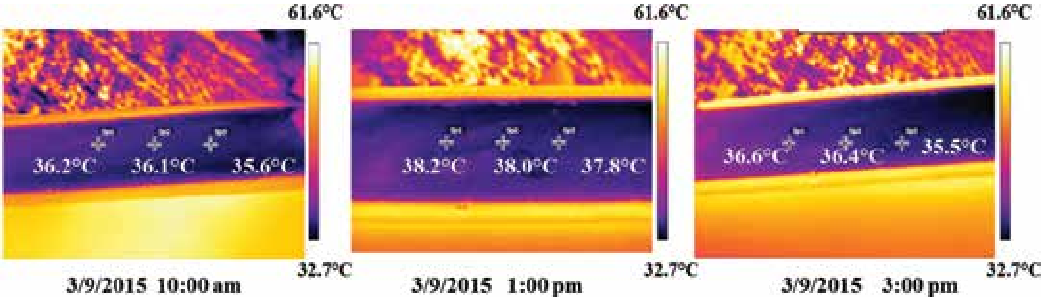

Figure 8. The variation of glass surface temperatures in the solar chimney.

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.

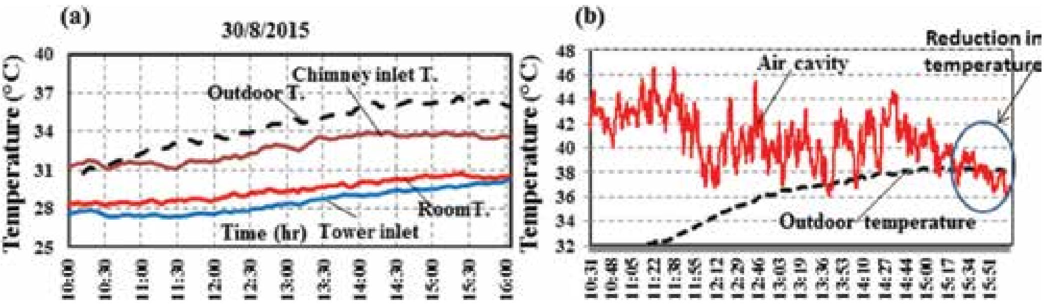

Figure 9. (a) The variation between tower inlet temperature, room temperature and chimney inlet temperature based on the cooling effect. (b) The temperature difference between chimney air cavity and outdoor temperature.

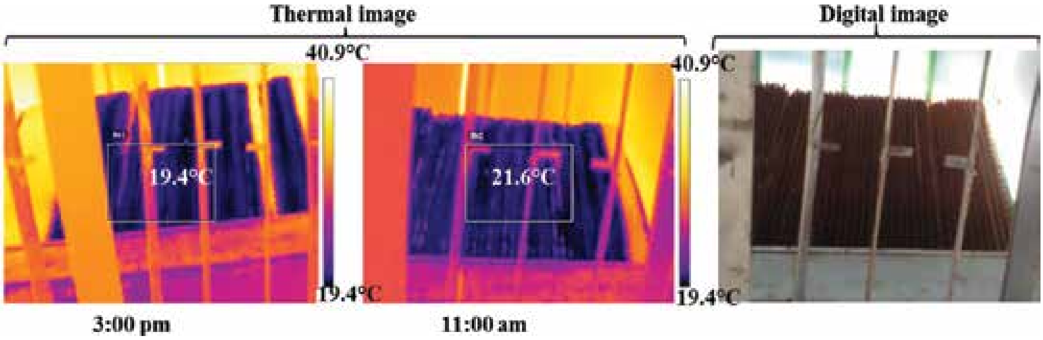

Figure 10. The variation of expanded paper surface temperatures (cooling pad).

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

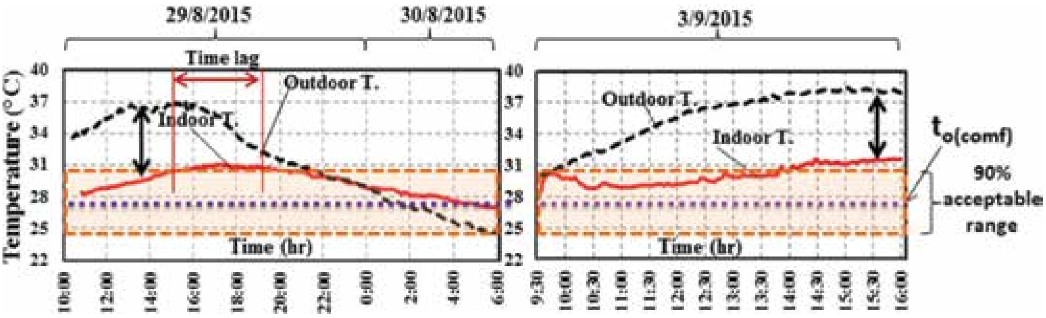

Figure 11. Temperature profile for indoor environment with a cooling technique compared to outdoor condition on the 90% acceptable range of adaptive comfort standard.

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

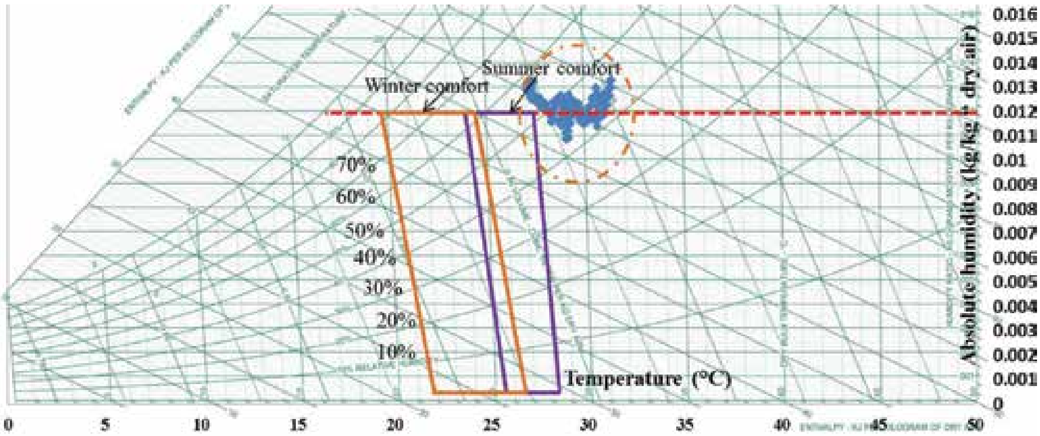

Figure 12. Temperature and humidity conditions inside the room after using the SCPC system.

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.

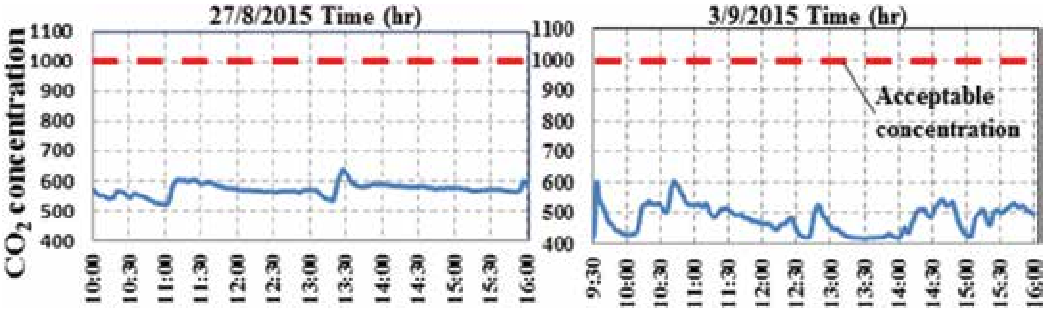

Figure 13. Indoor CO_2 concentration inside the room with SCPC system.

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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Chapter 6

Biogas Production from Brown Grease and the Kinetic Studies

Pengchong Zhang

Additional information is available at the end of the chapter

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Abstract

Food wastes were mostly treated in landfills due to economic reasons, which create rich organic leachate and soil contamination risks. An alternative for food waste treatment is to use the anaerobic digestion technique to reduce the organic content, as well as to recover bioenergy in the form of biogas. In this chapter, a common type of food waste brown grease was selected and investigated using a pilot-scale high-rate completely mixed digester, and the digestibility, biogas production, and the impact of blending of liquid waste streams from a nearby pulp and paper mill were assessed. Using a pseudo-first-order rate law, the observed degradation constant was estimated to be 0.10–0.19 d^{-1} compared to 0.03–0.40 d^{-1} for other organic solids. These results demonstrate that brown grease is a readily digestible substrate that has excellent potential for energy recovery through anaerobic digestion.

Keywords: brown grease, biogas, anaerobic digestion, renewable energy

1. Introduction

Biogas as an alternative source of energy is gaining more traction throughout several nations of the world [1]. Researchers have been conducting massive experiments on evaluating the conversion of miscellaneous wastes like animal manure, municipal solid waste, energy crops, municipal biosolids, food waste, and so on to biogas [2–4]. Biogas as an end-product could be produced from either artificially engineering anaerobic digester processing or naturally through the organic waste decaying process. Both the artificial and natural processes will include the main steps in anaerobic digestion; these are: hydrolysis, acidogenesis, and methanogenesis. Optimization of biogas generation from artificially engineering the anaerobic system is centrally focused on the digester design and operation, although it has been stated that the feedstock is as important as the digester technology.

A type of food waste, brown grease (BG) was selected here for investigation. In the United States, there are 3800 million pounds of trap grease produced every year (per National Renewable Energy Laboratory Report [5]). Considering 100% conversion efficiency, approximately 14 million m^3 of methane could be generated from these grease wastes [6, 7]. This substantial amount of energy could be used in different ways. Also, the environmental effect would be minimized compared to the effect of dumping to landfills [8].

BG is a mixture of fat, oil and grease from animal fat, vegetable oil, and other grease typically found in grease interceptors in restaurants and food industries [9]. Most of the time BG will be disposed to landfill, as the landfill treatment cost is only 5 cents per pound of brown grease [5]. However, landfills will generate some side effects such as soil and water pollution; these side effects will make the soil sterile and unusable to support plant life [5] and then garner ever-growing environmental concerns. These problems have a significant negative impact on the industrial cost and environmental effect of the BG treatment processes [10]. Anaerobic digestion technique is a viable option of the BG treatment [11]. The benefits of using anaerobic digestion include that the technique requires less reactor size, eliminates off-gas air pollution, produces less sludge, and generates substantial amounts of biogas as energy recovery; the generated biogas could then support the plant operation after converted to mechanical energy [12–14]. However, nowadays, only a small portion of BG has been treated by anaerobic digestion process, mainly because the biogas energy benefit cannot meet the anaerobic process investment [15, 16].

Kinetic simulation models of the anaerobic digestion process have been used to predict the digestion patterns and help to optimize design parameters of digestion reactors. As we have known that anaerobic digestion is a complex microorganism reaction process, to simplify the model, a pseudo first-order kinetic model can be applied to provide information, such as the relationship between feed rate and reactor size, and so on.

In this chapter, the biogas forming potential of BG as well as its COD and solids removal efficiency during the anaerobic digestion process was illustrated; moreover, system kinetic study has been performed to estimate the effects of input variations and substrate composition to the overall stability of the process. To make the investigation more comprehensive, various substrates from paper mill including foul condensate (FC) and screw press liquor (SPL) have also been introduced. The process parameters including substrate composition, hydraulic retention time (HRT), organic loading rate (OLR), and others have been studied in the process to get the optimal value.

2. Methodology

The anaerobic digestion system employed in this chapter includes three CSTR tanks: balance tank (BAL), facultative tank (FAC), anaerobic digester (AD), and a final batch sedimentation tank (ST). The raw substrate streams were equalized in BAL and then been fed to FAC for bioaugmentation and predigestion, then the predigested substrates were pumped continuously into AD for digestion. During the treatment process, the mixing condition in AD vessel was checked periodically to confirm the accordance of sample. The BAL and FAC tanks were always operating under an internal mixing condition so that the *p*H adjusting and grease hydrolysis would be favored.

The whole evaluation process takes 343 days. Due to system maintenance recovery and feeding transition issues during the operation, five periods (S1–S5) of stable system performance were selected for assessment. **Table 1** summarizes the divided evaluation periods and correlated operating parameters. During each operating period, a steady-state operation was selected for further analysis. The settling tank was introduced at the 196th day. In S3 and S5, FC and SPL was fed as a cosubstrate to investigate their impact for the system.

The characteristics of BG, FC, and SPL were listed in **Table 2**. BG used in this study was obtained from a food waste plant in Houston, TX. Before feeding to the BAL, the stream was prescreened and the rest was dehydrated; lime was introduced to increased pH to neutral (see **Table 2**) in order to maintain the minimum microorganism activity; afterward, the BG was shattered by a beater to ensure complete emulsification with tap water.

	System start-up	**S1**	**S2**	**S3**	**S4**	**S5**
Date	4/13/11–7/26/11	7/27/11–8/7/11	8/8/11–10/24/11	10/25/11–12/7/11	12/8/11–2/29/12	3/1/12–3/21/12
Days of operation (d)	/	1–12	13–90	91–135	136–217	218–238
Days with consistent data (d)	/	1–12	34–43	107–133	184–217	218–238
Settling tank	No	No	No	Yes	Yes	Yes
Feeding	BG	BG	BG	BG + FC	BG	BG + SPL
Influent COD (mg L^{-1})	/	19,208 ± 1579	26,205 ± 2685	26,570 ± 6264	33,881 ± 9176	30,200 ± 1503
Influent VS (mg L^{-1})	/	10,367 ± 662	12,802 ± 925	10,139 ± 754	13,224 ± 3236	13,225 ± 1891
OLR*	/	2.0 ± 0.2	2.0 ± 0.2	0.8 ± 0.2	0.6 ± 0.2	0.9 ± 0.3
HRT*	/	7.3 ± 0.6	11.9 ± 1.1	15.2 ± 1.1	15.8 ± 1.9	11.0 ± 0.1
Activity	Seeding and initiating	Establish BG steady state	Reduce flow rate	Establish BG + FC steady state	Maintenance and recovery	Establish BG + SPL steady state

*OLR and HRT in S1 and S2 were calculated based on digester only (considering recycle); OLR and HRT in S3–S5 were calculated based on digester + sedimentation tank (not considering recycle).

Table 1. Feeding schedule and operating periods.

Parameter	**Brown grease (BG)**[a] (μ ± σ, n = 17)	**Foul condensate (FC)** (μ ± σ, n = 11)	**Screw press liquor (SPL)** (μ ± σ, n = 13)
COD (mg L^{-1})	910,634 ± 229,993	2973 ± 142	4498 ± 2020
dCOD (mg L^{-1})	/	2740 ± 125	609 ± 189
TS (mg L^{-1})	437,778 ± 91,348	406 ± 104	8768 ± 7957
VS (mg L^{-1})	372,111 ± 77,646	210 ± 14	3742 ± 1666
VS/TS ratio	0.85 ± 0.06	0.53 ± 0.1	0.5 ± 0.1
TSS (mg L^{-1})	/	357 ± 577	4048 ± 1750
VSS (mg L^{-1})	/	339 ± 461	1997 ± 875
VSS/TSS ratio	/	0.83 ± 0.25	0.49 ± 0.06
Alkalinity (mg L^{-1} as $CaCO_3$)	/	205 ± 50	/
*p*H[b]	6.51 ± 0.77	9.28 ± 0.18	8.44 ± 0.83
TN (mg L^{-1})	/	52.2 ± 4	2.3 ± 0.1
TP (mg L^{-1})	/	0.24 ± 0.09	0.41 ± 0.04
Sulfide (mg L^{-1})	/	52.2 ± 20.5	/
Sulfate (mg L^{-1})	/	<40	/
Moisture content (wt%)	56 ± 9	/	/

[a] In BG, COD, TS, and VS are measured as mg/kg.

[b] pH of BG was measured by suspending 100 g BG in 1 L tap water. Tap water has pH of 8.05 and alkalinity of 55 mg L^{-1} as $CaCO_3$.

Table 2. Substrate characteristics.

During S3 and S5, instead of mixing with tap water, FC and SPL were introduced as cosubstrate, respectively. Compared with BG, FC and SPL have a relatively low COD concentration and solids content (see **Table 2**). Also, since BG contains enough amount of total nitrogen (TN) and total phosphorous (TP) for anaerobic digestion, no additional nutrients were added to the batch.

3. Results and discussion

3.1. Performance of anaerobic process

The summary of anaerobic operating parameters and results was listed in **Table 3**. For comparison purpose, typical values for anaerobic digestion processes were also listed. During the entire process, the *p*H in digester has been controlled at the neutral range (7.01–7.34, optimal *p*H range for anaerobic digestion 6.9–7.6) and the digestion occurred mostly at mesophilic temperature (34.3–37.9°C). The low DO concentration (< 0.1 mg L^{-1}) and ORP value (<–200 mV) indicate that the system is strictly anaerobic. VFA concentration is lower than

Operating periods	S1	S2	S3	S4	S5	Typical range
*p*H	7.34 ± 0.05	/	7.12 ± 0.08	7.10 ± 0.07	7.01 ± 0.17	6.5–8.5
T(°C)	36.0 ± 0.7	36.3 ± 0.7	34.3 ± 1.8	34.3 ± 2.1	37.9 ± 1.0	35–40
DO (mg L^{-1})	0.01 ± 0.00	/	0.06 ± 0.04	0.15 ± 0.05	0.10 ± 0.03	/
ORP (mV)	−209 ± 14	−228 ± 24	−243 ± 40	−247 ± 37	−263 ± 23	−400 to −150
TN (mg L^{-1})	591 ± 83	409 ± 37	237 ± 74	314 ± 50	306 ± 46	60–1000
TP (mg L^{-1})	3.4 ± 2.4	1.5 ± 0.4	0.9 ± 0.4	2.3 ± 1.1	2.2 ± 0.4	6–50
Alkalinity (mg L^{-1} as $CaCO_3$)	3087 ± 282	/	1455 ± 457	2478 ± 291	2204 ± 222	1500–5000
VFA (mg L^{-1} as HAc)	274 ± 97	/	199 ± 76	394 ± 84	629 ± 378	<1800
COD removal efficiency (%)	42.1 ± 6.7	50.6 ± 5.8	82.3 ± 11.0	61.7 ± 12.3	53.5 ± 8.7	/
VS removal efficiency (%)	26.8 ± 7.9	37.1 ± 4.3	70.1 ± 8.4	65.6 ± 7.0	62.3 ± 7.2	/
CH_4 content (%)	74.3 ± 2.0	74.6 ± 1.0	75.9 ± 1.9	74.6 ± 1.8	75,4 ± 1.0	/
CO_2 content (%)	22.3 ± 1.3	/	23.9 ± 1.9	25.2 ± 1.8	24.2 ± 1.0	/
H_2S content (ppm)	38.2 ± 4.1	/	147.2 ± 34.8	185.2 ± 28.1	371.7 ± 127.6	/
CH_4 yield (m^3-CH_4 Kg-VS^{-1})	0.99	0.66	0.52	0.48	0.45	0.30–1.00

Table 3. Operating conditions in each period.

400 mg L^{-1} as HAc except S5 when the VFA level is somewhat elevated up to 630 mg L^{-1} as HAc. TN and TP concentration in system is 230–600 mg L^{-1} as N and 1–4 mg L^{-1} as P respectively, which indicates enough nitrogen but slightly lower in phosphorus concentration.

Figure 1 shows the COD and VS variation and removal efficiency during each operating period. During S1 and S2, the ST has not been introduced to system yet, the effluent from AD was considered as final effluent and some of the sludge from AD was recycled to FAC manually that results for the higher effluent COD concentration (20,000–30,000 mg L^{-1}) compared with other stages (~10,000 mg L^{-1}). The COD removal efficiency in these periods is relatively lower than other periods, about 30–60% (**Figure 1a**). After ST was added (S3–S5), the effluent COD was kept in a relatively stable range (~10,000 mg L^{-1}) even if the influent COD was varied from 15,000 to 80,000 mg L^{-1} (**Figure 1a**). This implies that sedimentation tank was efficiently in the elimination of a substantial amount of COD and polishing the quality of final effluent. With the stable effluent COD, during S3, FC was added as a cosubstrate and the initial COD loading was increased; thus, the COD removal efficiency was increased (70–95%, **Figure 1a**) to the highest value in the overall process.

During each operating period, VS variation has a similar trend with COD; the VS removal efficiency during S3–S5 did not change too much, in the range of 40–70% (**Figure 1b**), while the effluent VS concentration in S4 seems higher that may be due to the higher influent VS concentration. After added the ST, the VS removal efficiency was also improved from 20–40% to 40–70% (**Figure 1b**).

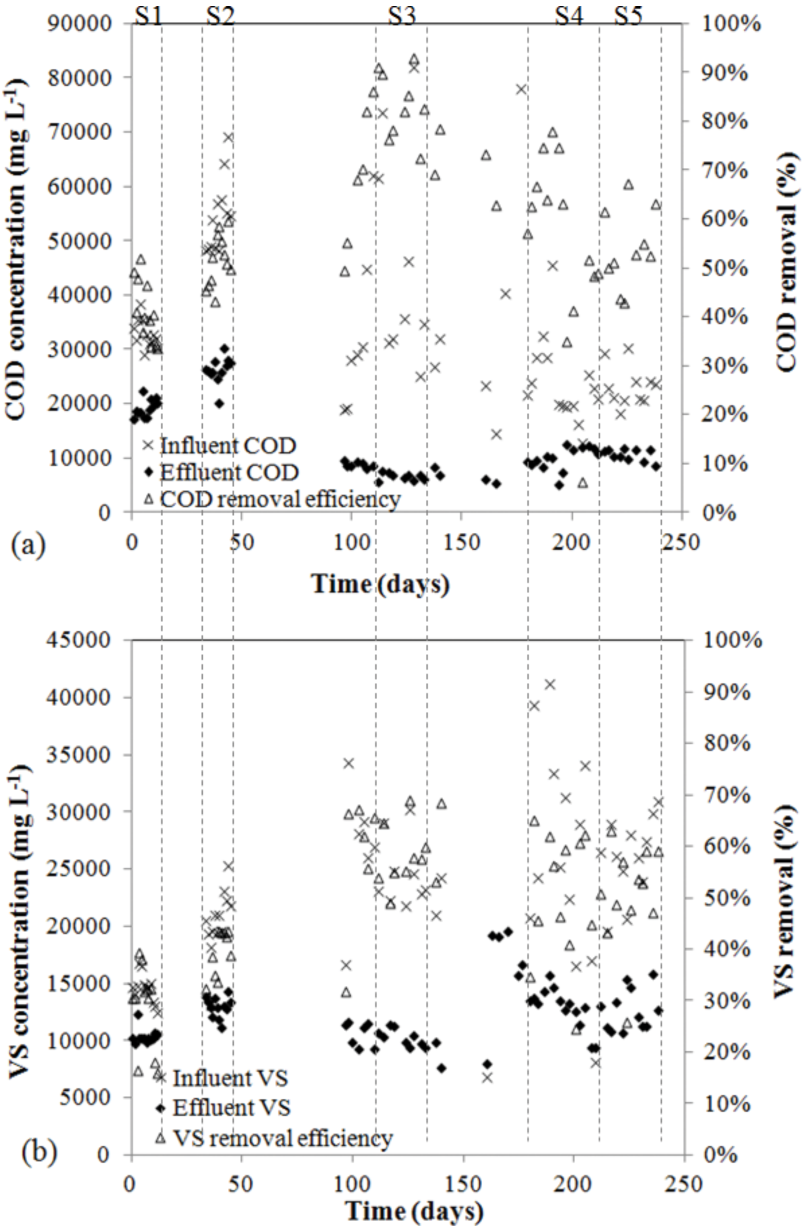

Figure 1. COD (a) and VS (b) concentration variation before and after AD, and their removal efficiency. Five stable operating periods (S1–S5) were marked.

The indicator of system organic removal is the volatile ratio (VS/TS and VSS/TSS) before and after AD. **Figure 2** shows the VS/TS ratio (**Figure 2a**) and VSS/TSS ratio (**Figure 2b**) in FAC and AD, respectively. In FAC, the volatile ratio is 0.84–0.86, and this ratio decreases to 0.66–0.69 in AD. The reduced ratio indicates that there was organic digestion since the inorganic parts should always be consistent in the anaerobic digestion process. Compared with the

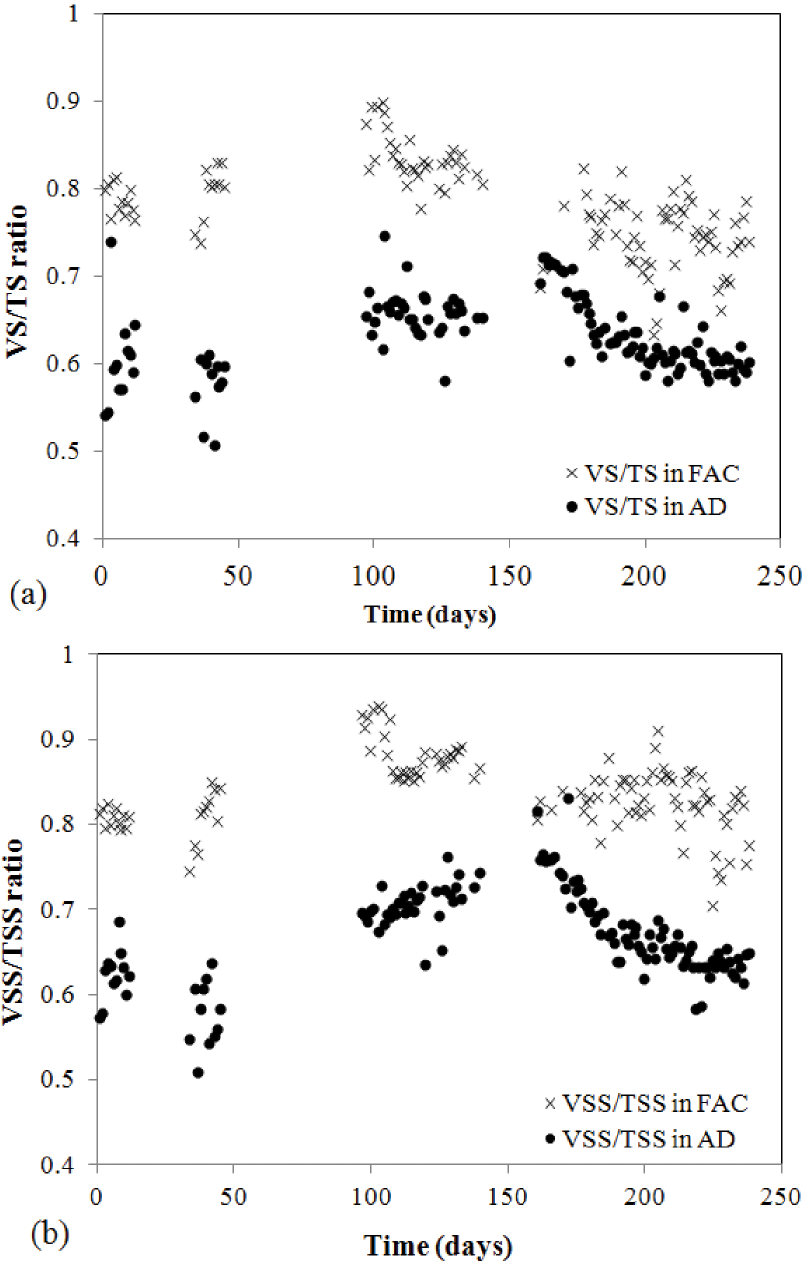

Figure 2. Volatile fraction including VS/TS (a) and VSS/TSS (b) in both FAC and AD.

dCOD reduction from FAC to AD (see **Table 3**), the decrease of volatile fraction should come of hydrolysis, acidogenesis, and methanogenesis together.

Figure 3 shows the scattered plot between system organic removal and organic loading rate in terms of COD (**Figure 3a**) and VS (**Figure 3b**). In S1 and S2, the OLR is higher than S3–S5 since the clarifier was not included and the OLR was calculated with considering the recycling

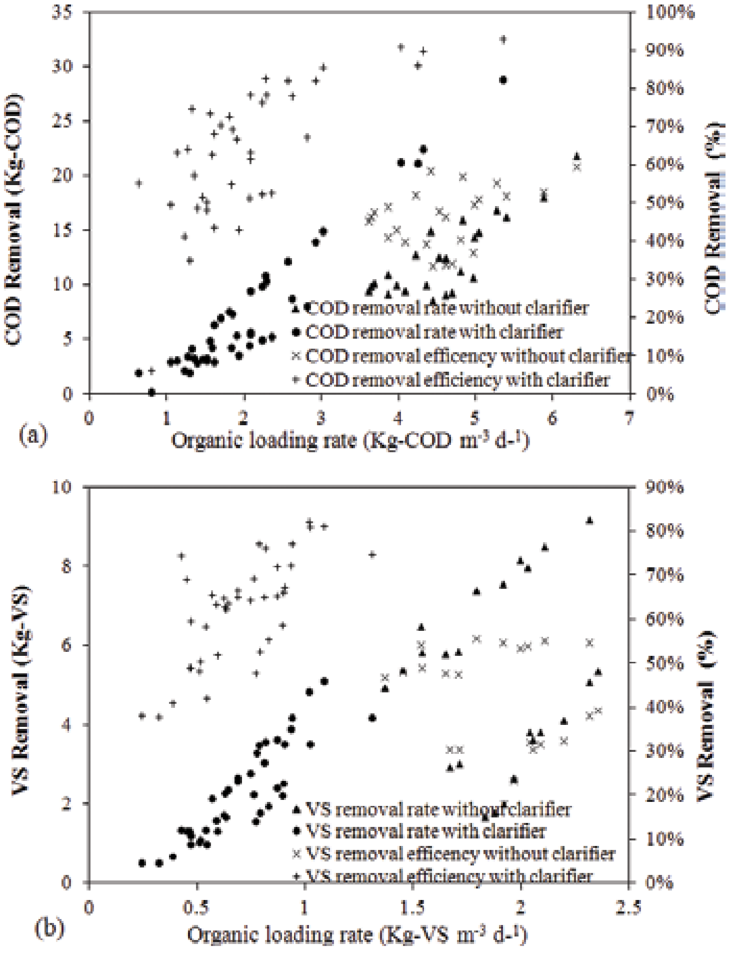

Figure 3. Scatter plots between organic loading rate and organic removal in terms of COD (a) and VS (b).

sludge. Both on COD and VS, the removal efficiency was not significantly affected by OLR variation, resulting in linear increase of COD and VS removal with respect to the applied OLR. This indicates that the system throughput could be improved within the OLR range applied during the evaluation periods to obtain higher organic removal efficiency.

VFA is also an important parameter to investigate the anaerobic process. As the source for methanogenesis, the system needs a certain amount of VFA; while VFA accumulation to greater than 1800 mg L^{-1} has been shown suggested to significantly decrease *p*H and *in vitro* toxicity, thus somewhat alkalinity was needed to offset the extra amount of VFA as well. **Figure 4** shows the VFA concentration in FAC and AD as well as the alkalinity in AD. The mean alkalinity during overall process is 2122 mg L^{-1}, which is adequate for extra VFA. As shown in **Figure 4**, when substrate moves from FAC to AD, the average VFA concentration decreased from 800 to 413 mg L^{-1}, which indicates that FAC was efficiently augmenting VFA generation and improving the methanogenesis process in AD.

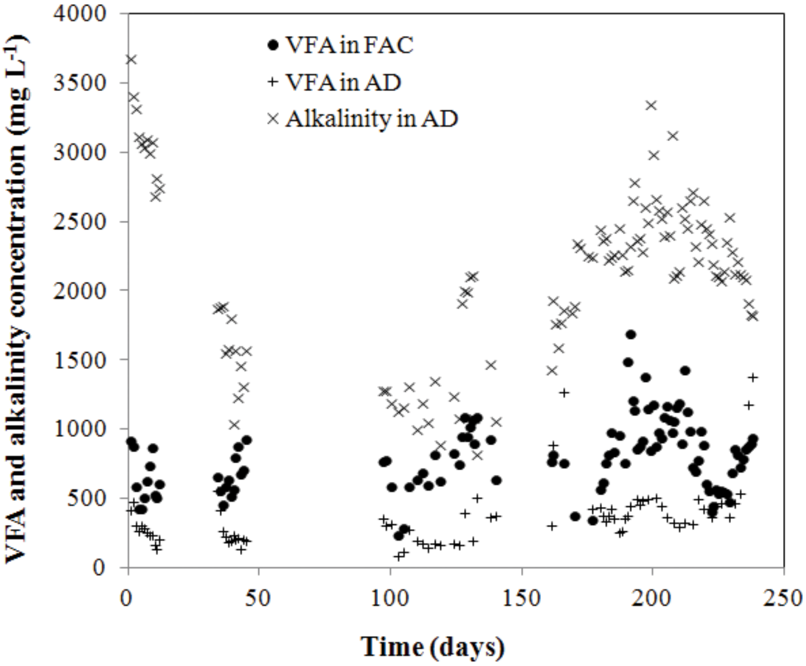

Figure 4. VFA variation before and after AD, and alkalinity level in AD.

3.2. Methane yield and kinetic analysis

The produced biogas has a consistently high CH_4 content (~75%, see **Table 3**). The other major gas (CO_2) consisted of the other ~25% by volume (**Table 3**) and trace gases (e.g., H_2S). From day 160–175, the system was recovered from system maintenance and the methane content built up from 40% to 75% quickly (**Figure 5**). During the entire evaluation, the average H_2S concentration was 189 ppm, significantly lower than that level that may cause H_2S toxicity (~1500 ppm).

The cumulative CH_4 production and digested VS in S3–S5 are shown in **Figure 6**. The methane yields of S3–S5 were calculated directly as the ratio of the two slopes. The value was reported based on VS removal because the organic content of the BG feed was mainly in the suspended solid phase. The methane yield of BG in S3–S5 was consistent in the range of 0.45–0.49 m^3-CH_4 Kg-VS^{-1} (at standard temperature and pressure, STP). All the gas volumes mentioned hereafter have been normalized to STP.

For the first two stages (S1 and S2), the apparent VS removal efficiency (25–40%, **Table 3**) was significantly lower than in S3–S5 (55–75%, **Table 3**) because ST had not been introduced to the system. Based on that, the effluent VS during S1 and S2 contains a large amount of biomass produced from the anaerobic digestion of brown grease. During S3–S5, ST was used to collect and recycle most of the generated biomass back to the AD, resulting in the higher organic removal efficiency. To estimate the BG conversion into biogas during S1 and S2, a mass balance analysis on solids before and after the AD was performed as follows:

$$(1-f)F = (1-\alpha)X + (1-\beta)Y \tag{1}$$

$$\alpha X + \beta Y = M \tag{2}$$

Eq. (1) represents the mass balance of the inorganic (fixed) solids where f is the volatile fraction of influent BG obtained from measurement (0.808 in S1 and 0.816 in S2), F is the mass flow of influent total solid (Kg d^{-1}), α and β are the volatile fraction (VS/TS) of biomass and undigested BG substrate, respectively ($\alpha \approx 0.80$). X and Y are the mass flow of biomass and undigested BG, respectively (Kg d^{-1}). Eq. (2) represents the VS composition in the effluent, where M is the mass flow of VS in the effluent (Kg d^{-1}). Using the solid measurements, we estimated that the generated biomass constitutes 25–50 wt% in the effluent.

Based on the mass balance results, the cumulative CH_4 production and the digested VS during S1–S5 were plotted in **Figure 6**. The methane yield was then calculated as the ratio of the slopes of the two lines in the respective period. The estimated methane yield in S1 (0.40–0.49 m^3-CH_4 Kg-VS^{-1}) was comparable with S3–S5 (0.45–0.49 m^3-CH_4 Kg-VS^{-1}). S2 has a higher methane yield (0.58–0.77 m^3-CH_4 Kg-VS^{-1}) at the cost of lower organic removal at higher organic loading (**Table 3**), which would require greater treatment effort for the digester effluent. During S3–S5, the organic removal was obviously higher with reduced methane yield. Therefore, the mode of process operation will depend on the treatment objective (better organic removal or higher methane yield). Also, the added cosubstrate (FC and SPL) did not adversely affect the methane yield during S3–S5 (**Table 3**).

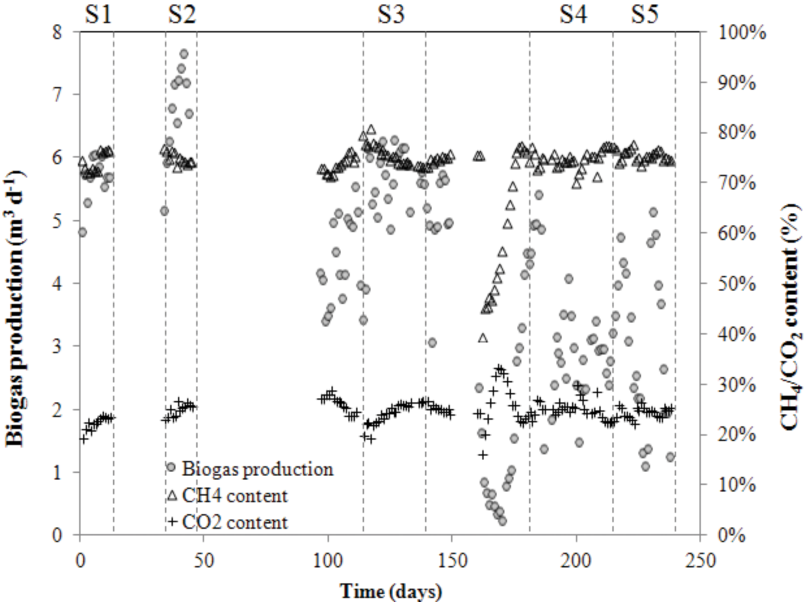

Figure 5. Measured daily biogas production and CH_4/CO_2 content.

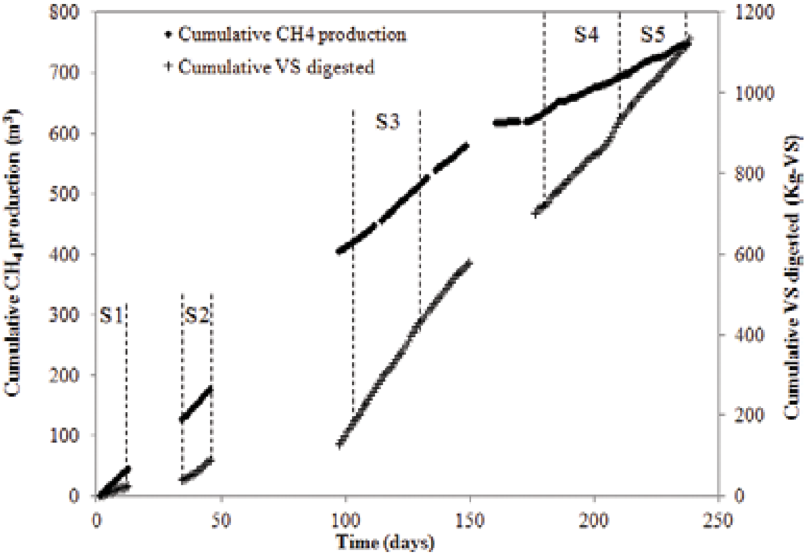

Figure 6. Cumulative CH4 production at STP and cumulative VS digested during five selected stages (S1–S5). The slopes of each linear stage were used to calculate corresponding CH4 yield. In S1 and S2, the mass of digested VS was corrected by biomass calculation.

A pseudo-first-order kinetic model was applied to analyze the substrate utilization. Similar approaches have been used earlier [2, 17]. The substrate concentration was calculated based on VS. For a CSTR at a steady state, the effluent concentration (*C*) can be estimated as:

$$C = \frac{Co}{1 + k\theta} \tag{3}$$

where C_0 is the influent substrate concentration (mg L^{-1} VS), *k* is the first-order substrate utilization rate constant (d^{-1}), and θ is the HRT (d). The estimated *k* value is in a relatively consistent range of 0.10–0.19 d^{-1} throughout the evaluation process.

For comparison purposes, the previous reported methane yields of food wastes and their first-order kinetic parameters are shown in **Table 4** [18–25]. Different degradation rate constants were obtained for different substrates and bench-scale reactors. Generally, the rate constants were in the range of 0.03–0.4 d^{-1}. The rate constant obtained in this study (0.10–0.19 d^{-1}) has probably been adversely affected by the greater difficulty of controlling the digestion conditions (temperature and mixing) in a pilot-scale system due to the ambient temperature variation (>15°C diurnal change). It was slightly lower than that of municipal solid sludge in batch reactors (0.2–0.4 d^{-1}), comparable to that of municipal solid sludge in CSTR (0.175 d^{-1}), and higher than that of canary grass in CSTR (0.03–0.04 d^{-1}). The methane yields in this study range from 0.45 to 0.85 m^3-CH_4 Kg-VS^{-1}, higher than earlier reported data (0.11–0.42 m^3-CH_4 Kg-VS^{-1}, **Table 4** [18–25]) from food wastes in solid digesters. The biogas quality produced by BG is excellent (~75%, **Table 3**), possibly due to the high lipid content of BG. These pilot-plant data suggest that BG can be effectively digested anaerobically for high-quality biogas production.

Substrate	Reactor type	Pseudo-first-order rate constant (d^{-1})	Methane yield (m^3-CH_4 Kg-VS^{-1})
Brown grease	CSTR	0.10–0.19	0.40–0.77
Municipal sludge	CSTR	0.175	0.309
Municipal sludge	Batch	0.2–0.4	/
Corn stover	Batch	/	0.239
Rice straw		/	0.225
Canary grass	CSTR	0.03–0.04	0.19–0.33
Sunflower oil cake	Batch	/	0.107–0.227
Winter wheat	Batch	/	0.311–0.360
Waste activated sludge	Batch	/	0.116
Waste activated sludge + fatty wastewater	Batch	/	0.362
Synthetic kitchen waste	Batch	/	0.117
Synthetic kitchen waste + municipal grease waste	Batch	/	0.324–0.418

Table 4. Comparison of reported and calculated first-order degradation rate constants and methane yields [18–25].

4. Benefits of anaerobic digestion process of BG

In this chapter, the anaerobic digestion process of BG as well as its kinetic study was investigated. An average COD removal of 58% and VS removal of 55% was achieved. The organic removal efficiency was consistent and comparable with earlier studies. Kinetic analysis indicated that the pseudo-first-order degradation rate constant of BG was in the range of 0.10–0.19 d^{-1}.

The organic removal rate and kinetic coefficient listed above indicate that anaerobic digestion process could be introduced as an effective pretreatment process of BG for initial COD removal and energy recovery. After anaerobic treatment process, the effluent had a consistent effluent organic strength (COD ~ 10,000 mg L^{-1}) that can be treated aerobically. Based on the analysis, BG was found to be a readily digestible substrate. The recovered biogas could be considered as a readily in-plant-usable energy source; therefore, the energy utilization efficiency will be increased, and also the capital of organic treatment will be decreased, which is an industrial win-win situation. Once the AD process was linked as a gate-to-gate life cycle to the BG treatment chain, the efficiency of the complete cradle-to-gate evaluation will be improved and the total cost will be reduced.

The pilot-scale system produced excellent quality biogas (75% CH_4 content), with a methane yield in the range of 0.40–0.77 m^3-CH_4 Kg-VS^{-1}. The addition of paper mill waste streams (FC and SPL) as cosubstrate did not adversely affect the methane yield. Currently, anaerobic digestion technique has not been widely used in the pulp and paper industry due to the recalcitrant nature of the paper process wastes. However, the combining treatment process of paper process and food process wastes does not show negative affections and could be considered as an alternative treatment method in the future.

The conclusion of this chapter is that BG has the industrial potential to be anaerobically treated as an energy feedstock and there has been ongoing commercial effort to build large-scale digesters using BG as the primary substrate. Using BG for biogas production could serve as a profitable model for converting waste to renewable energy.

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Section 3

Environmental Impact

Chapter 7

Impacts of Bio-Based Energy Generation Fuels on Water and Soil Resources

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Additional information is available at the end of the chapter

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Abstract

The use of bio-based fuels for energy generation can have positive or negative impacts on water and resources. To best understand these impacts, the effects of bioenergy systems on water and soil resources should be assessed as part of an integrated analysis considering environmental, social and economic dimensions. Bioenergy production systems that are strategically integrated in the landscape to address soil and water problems should be promoted where their establishment does not cause other negative impacts that outweigh these benefits. While standardized metrics, such as footprints and water- and nutrient-use efficiencies are convenient and intuitive, these factors can be insufficient to achieving sustainable production and environmental security at relevant spatial and temporal scales. Comprehensive ecosystem impact analysis should be conducted to ensure that sustainability standards like water quality, water supply, and soil integrity are consistent with other agricultural and silvicultural sustainability goals at the local, regional, and global level.

Keywords: bioenergy, water quality, water supply, soil integrity, sustainability

1. Introduction

Water and soil are intimately linked ecosystem resources that provide the basic chemical requirements for plant life on earth (**Figure 1**) [1, 2]. The use of plant resources, for bioenergy or any other human purpose, must be viewed in the context of total ecosystem services and through the lens of long-term sustainability. In the current world, nearly one-third of the planet's land surface is dedicated to agriculture. This same land base accounts for nearly three quarters of the global freshwater use [3]. Because of this connectivity, bioenergy systems development poses

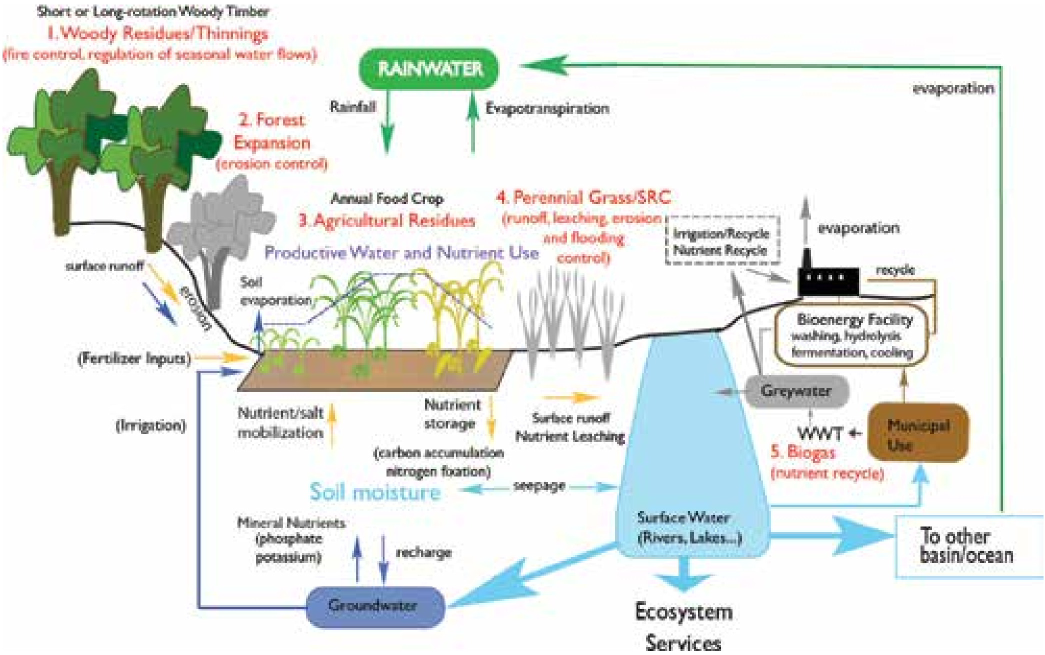


Figure 1. Linkages between bioenergy systems, soils, and water in an agroforestry landscape (From [2]).

significant challenges from the perspective of soil and water quality. At the same time, bioenergy systems present new opportunities to improve land and water sustainability and productivity, as well as addressing soil and water impacts produced by current land use.

1.1. Background

In the search to develop renewable energy, woody and agricultural crops are being considered as an important source of low environmental impact feedstocks for electrical generation and biofuels production [4–7]. In countries like the USA, the bioenergy feedstock potential is dominated by agriculture (73%) [8]. In others like Finland, the largest feedstock source comes from forest resources. Forest bioenergy operational activities encompass activities of a continuing and cyclical nature such as stand establishment, mid-rotation silviculture, harvesting, product transportation, wood storage, energy production, ash recycling, and then back to stand establishment [8]. All of these have the potential to produce disturbance that might affect site quality and water resources, but the frequency for any given site is low [9–12]. Agricultural production of feedstocks involves annual activities that have a much higher potential to affect soils and water resources. Since the rotational cycle for forestry is much less frequent, the potential for disturbance to water and soil resources is greatly reduced.

The way forward relative to assessing the soil and water impacts of bioenergy systems and the sustainability of biomass production rests with three approaches that could be used individually but are more likely to be employed in some combination [12]. These approaches are: (1) Utilizing characteristics that can be quantified in Life Cycle Assessment (LCA) studies by software, remote sensing, or other accounting methods (e.g. greenhouse gas balances, energy balance, etc.) [13]; (2) Measuring and monitoring ecosystem characteristics that can be evaluated in a more or less qualitative way (e.g. maintaining soil organic carbon) that might provide insights on potential productivity and sustainability, and (3) Employing other proactive management characteristics such as Best Management Practices (BMPs) that are aimed at preventing environmental degradation.

1.2. Life cycle assessment

Life Cycle Assessment has been used to estimate the environmental impacts of biomass energy uses. Typically they examine greenhouse gas (GHG) emissions, CO_2 emissions, energy balance, and some indirect effects. A review of published LCAs, revealed that more than half of the studies were from North America and Europe, and that most are found in papers published in scientific journals [9–11]. Increased numbers of South Asia, Africa, and South America can be found. About 50% of the studies limited the LCA to GHG and energy balances without considering contributions of bioenergy programs to other impact categories such as soils and water. The published studies concluded that there are a number of problems in currently used LCA approaches that make it impossible to quantify environmental impacts from bioenergy programs. Some of the key indirect effects issues strongly depend on local operations, vegetation, soil, and climate conditions that tend to make accurate assessment of environmental effects very problematic.

Although politicians and upper level managers claim that methods exist for assessing environmental impacts on soil and water, the scientific foundation for estimating indirect effects of bioenergy programs is constrained by the lack of adequate validation research, accurate assessment methods, and the relative infancy of the LCA process. It was clearly pointed out that determination of environmental outcomes of bioenergy production is complex and can lead to a wide range of results [11, 12]. This review clearly stated that the inclusion of indirect environmental effects in LCA represents the next research challenge and not the immediate incorporation into the assessment methodology.

1.3. Sustainability and productivity

The second approach for assessing soil and water impacts of bioenergy systems, and the sustainability of biomass production, is dependent on soil quality monitoring. This approach was developed as a means of evaluating the effects of forestry and agricultural management practices on soil functions that might affect site productivity [13, 14]. A number of soil physical, biological and chemical parameters, which have linkages to soil productivity have been proposed as forming a minimum monitoring set. The way forward relative to assessing soils impacts and the sustainability of biomass production systems rests with proactive proper soil management and not reactive monitoring for screening the condition, quality, and health of soils relative to sustaining productivity [15–17]. Evaluation of soil condition thus would lead to a time-trend analysis that can in turn be used to assess the sustainability of land management practices and bioenergy programs. Even though sustainability is the stewardship goal of land management, more specific definitions of its goals and attributes is often complex and open to considerable interpretation [18, 19]. Many scientists have attempted to answer the "what," "what level," "for whom," "biological or economic," and "how long" questions of sustainability. However, there is no absolute definition of sustainability, and that it must be viewed within the context of the human conceptual framework, societal decisions on the state of ecosystem to be sustained, and the temporal and spatial scales over which sustainability is to be judged [18]. In short, this approach is loaded with considerable uncertainty and lack of consensus.

2. Water impacts of modern bioenergy programs

Reporting of water impacts on ecosystems caused by the implementation of bioenergy systems is both variable and incomplete (**Figure 1**). While some assessments include only active human uses such as irrigation and water used in biofuel conversion processes, others include hydrologic processes such as evapotranspiration, infiltration, runoff, and baseflows, which are natural ecosystem processes influenced by human activity (**Figure 2**) [2]. Water limitations may reduce the opportunities to use bioenergy in some ecosystems. However, there are many situations where bioenergy may advance both socioeconomic and sustainable landscape objectives [9, 12]. The objective of good bioenergy management is to keep water flow on the right side of the diagram in **Figure 2**.

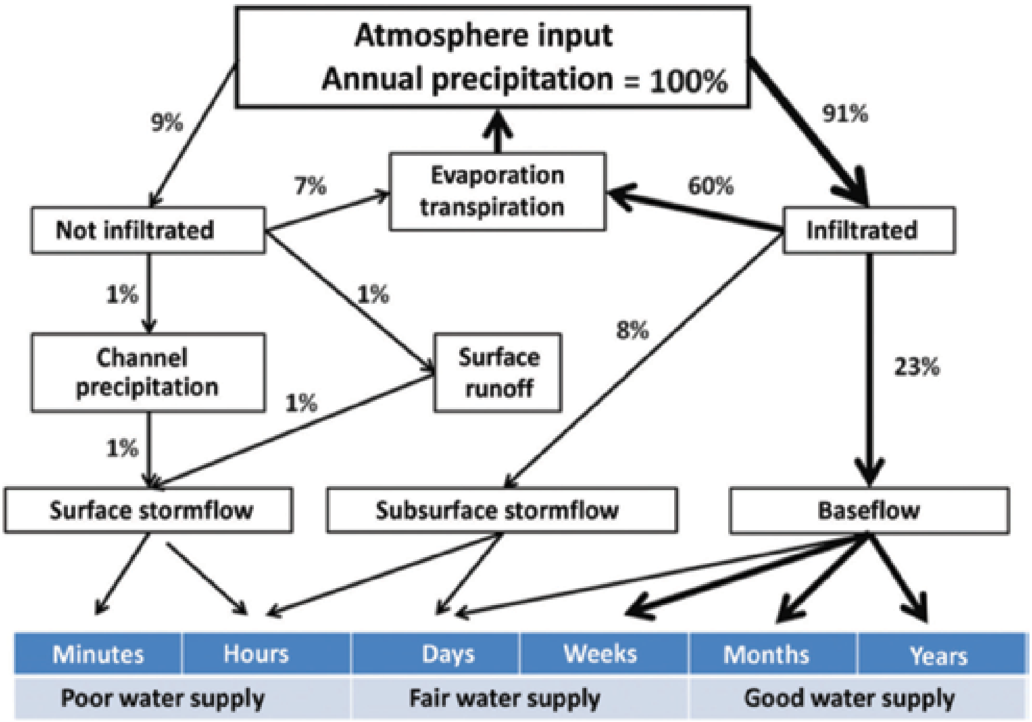


Figure 2. Hydrologic processes governing the water cycle and the distribution between desired good water supply, fair water supply, and poor water supply in ecosystems (From [12]).

2.1. Annual agricultural crops

The cultivation of conventional annual crops as bioenergy feedstocks affects soil and water resources similar to crop cultivation for food and livestock feed. Water withdrawals and the effects of agrochemicals must be carefully managed to avoid human health impacts, water quality degradation, and damage to ecosystems [20]. As in other agricultural and forestry activities, the adoption of BMPs is crucial to minimizing the risk of water quality impacts and promoting sustainable resource use. Assessing BMPs and their effectiveness further requires defining appropriate water quality expectations, determining what site conditions limit BMP effectiveness, and identifying the specific watershed characteristics and appropriate spatial and temporal scales for assessment [21].

2.2. Perennial and semi-perennial crops

Extensive root systems, long-term soil cover and protection, and reduced need for tillage and weed suppression, give semi-perennial crops excellent choices for bioenergy feedstocks. Crops such as sugarcane, perennial grasses like switchgrass, *Miscanthus* spp. and elephant grass, and trees grown in short rotations tend to have lower water quality impacts than conventional crops [22–24]. While many perennial crops considered for bioenergy have relatively high water use efficiency, their total water requirements can also be relatively large. Such crops are ideally suited to areas with high water availability and flows where water quality can be easily managed [25]. For example, one analysis indicated that that *Miscanthus* spp. could replace 50% of corn acreage in most areas of the Midwest US without adversely affecting the hydrologic cycle. In drier regions, *Miscanthus* spp. should be limited to 25% of the area [26]. Additionally, it has been suggested that the use of perennial grasses may increase seasonal evapotranspiration (ET) compared to grains due to the access of these grasses to moisture deeper in soil profiles [27].

2.3. Forest woody biomass

Forests provide important regulation of both water quality and seasonally available water quantity in most large watersheds. Forest bioenergy systems are judged compatible with maintaining high-quality water supplies in forested catchments. This general statement is true as long as BMPs that are designed for environment and resource protection, and include nutrient management principles, are followed [28–30]. While short term water impacts, including increased sediment, nitrates, phosphates, and cations can occur, there is no evidence of long term adverse impacts in forest catchments subject to normal management operations [12]. However, more research is needed to guide BMPs concerning special activities in forest management (e.g. stump extraction, weed control, and forest fertilization [29, 31]. Quantitative water flows in forest stands are affected if stands are subject to operations involving significant basal area reductions. But since a forest estate typically is a mosaic of stands of different ages, where only a small share of all stands are harvested in a particular year, water flow regimes on the larger landscape level typically are not affected significantly by stand level operations. Exceptions occur where forests are replaced with other land covers or more intensively managed tree crops.

2.4. Organic residues

Secondary and tertiary waste biomass (e.g. municipal wood waste, food processing waste, manures, and wastewater with high organic content) has the potential to improve water quality in communities by reducing landfill deposits, and leachates. However, utilization of this resource remains inefficient. Even with zero landfill policies and a Waste Framework Directive, the EU-28 countries recovered energy from only 7% of its non-recyclable municipal waste in 2011 [32]. Currently, use of primary waste biomass (e.g. harvest residues, forest thinnings, and slash) for energy is limited because of the economics of transporting these residues. Increased use of wood residues can improve land and water productivity but requires that site-specific conditions (e.g., soil, climate topography, etc.) and competing uses (e.g., animal feed and bedding) are considered.

2.5. Algae

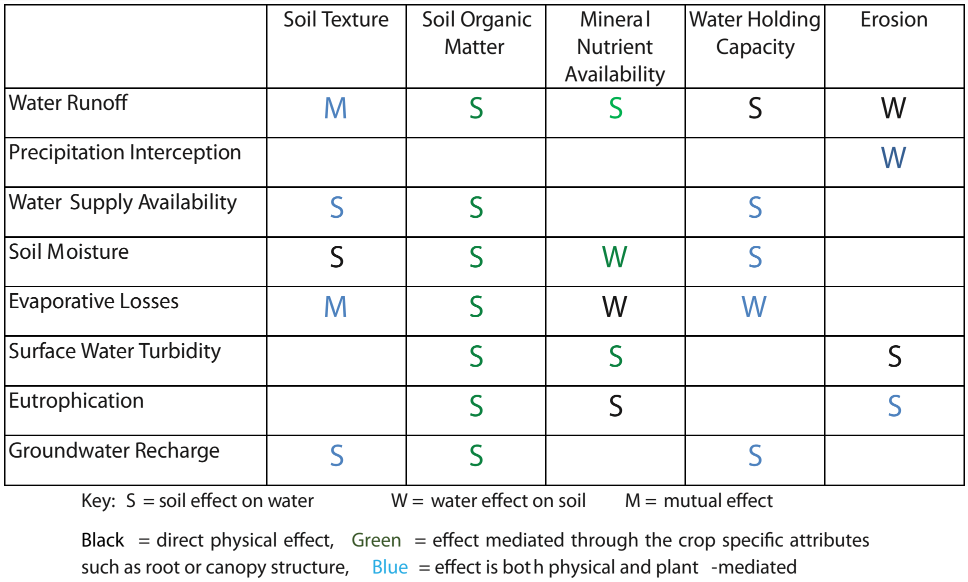
The water impacts of algal propagation vary widely by technology and environmental conditions, with water use ranging from minimal up to 3,650 $\mathrm{L\ L^{-1}}$ of biodiesel or advanced biofuel produced [33]. Freshwater is needed to replace water losses from open ponds, even when halophilic organisms are used. While the volumes in photobioreactors are relatively small, cooling requirements, usually met by freshwater, are large. Water impacts of conversion technologies result from competition from often scarce freshwater supplies.

2.6. Electrical generation impacts

In general, water impacts of biomass powered electricity generation remain similar to fossil fuel pathways, with large water withdrawals but low consumptive use ranging from 0–1800 $\mathrm{L\ MWh^{-1}}$ [34]. Cooling water, which may contain some salts, is returned at higher temperature to the source stream or basin, with variable ecological impact. Water requirements for biofuel processing continue to improve. Use per tonne of feedstock has decreased dramatically for both corn and sugarcane ethanol. For instance, the consumptive water use of ethanol-sugar mills in Southeast Brazil has decreased from 15 $\mathrm{m^3\ Mg^{-1}}$ of sugarcane bagasse prior to 2008 to $<3\ \mathrm{m^3\ Mg^{-1}}$ in 2008 [35]. However, in water stressed regions new or expanded facilities may still not be approved due to the associated water demand [35]. While, untreated effluent can create water quality problems, process water offers an opportunity to recover and recycle nutrients. Biofuel facilities with zero liquid discharge have been operating in the U.S. since 2006 and continue to expand worldwide. Technological improvements in water recovery and recycling have progressed to the point that some facilities are able to use municipal wastewater and some have achieved closed loop recycling of process water.

3. Soil impacts of modern bioenergy programs

Soils are a critically important, basically non-renewable ecosystem resource, that provide the physical, biological, chemical, and hydrologic foundation for agricultural and forest bioenergy feedstocks production [36–38]. Soils are able to redevelop after being degraded but the



	Soil Texture	Soil Organic Matter	Mineral Nutrient Availability	Water Holding Capacity	Erosion
Water Runoff	M	S	S	S	W
Precipitation Interception					W
Water Supply Availability	S	S		S	
Soil Moisture	S	S	W	S	
Evaporative Losses	M	S	W	W	
Surface Water Turbidity		S	S		S
Eutrophication		S	S		S
Groundwater Recharge	S	S		S	

Key: S = soil effect on water W = water effect on soil M = mutual effect

Black = direct physical effect, Green = effect mediated through the crop specific attributes such as root or canopy structure, Blue = effect is both physical and plant -mediated

Table 1. Interdependencies of water and soil resources (adapted from [2]).

time period might be several centuries or millenia, depending on climate and vegetation. Because of this long time factor, soils are considered to be non-renewable. They are heterogeneous and highly diverse components of ecosystems that form over long time periods under the influence of parent mineral material, climate, landscape position and biological activity.

As the base of bioenergy production systems, soils constitute a major factor that interacts with water to determine the type and amount of plant biomass production (**Table 1**, [2]). They provide the physical anchor which tie plants to the earth, supply water and mineral nutrients for plant growth, decompose and recycle organic material and residues and mediate hydrological processes [39–41]. Bioenergy feedstock systems are part of agricultural and forest management systems that provide multiple ecosystem products and services [42]. These include plant biomass, water flow, water quality control, biodiversity, cultural heritage, and carbon storage. Soils are important factors in each of these services. Therefore, it is critical that in the process of managing soils for bioenergy production, soils must be managed to sustainably provide a wide range of ecosystem services important to human communities. Maintaining the quality of soils will ultimately ensure maintenance of water quality.

4. Best management practices

The focus on renewable energy sources has raised concerns about environmental effects. In particular, the increase in the use of woody biomass, agricultural crops, agricultural residues and processing wastes residues as feedstocks for bioenergy production has intensified questions about potential impacts on water quality and soil sustainability. Intensification of forestry and agriculture raises concerns about cumulative effects on water quality and soil integrity [43]. Best Management Practices have been developed and implemented since the early 1970s to ensure that land management for wood fiber and agricultural crop production can be carried out with minimum impact on the environment [44]. Although BMPs were originally designed to minimize water quality impacts, they can be used ensure soil sustainability and biodiversity. The use of BMPs is widespread in developed countries and some developing nations. It varies from mandatory to voluntary depending on the degree of legislative support. For example, in many countries, BMPs are already incorporated in "Codes of Practice" that guide forest managers and farmers through the complete bioenergy life cycle. Best Management Practices have been developed and implemented in many agricultural countries to deal with water quality problems [44]. The use and implementation of BMPs is not a static process, but one that is dependent on a continual cycle of application, assessment and monitoring, refinement, and application. Although some countries have "national standards," the complex matrix of forest and agricultural ecosystems, climates, soils and topography, crop establishment and tending systems, and harvesting systems requires on-going evaluation and refinement to achieve BMPs to best fit local management and environmental conditions.

The rationale for BMP usage is multifaceted. Some of the reasons include: (1) State and National environmental regulations, (2) Agency regulations and goals, (3) Private land management objectives, (4) Land manager desires to seek certification for marketing purposes, (5) Corporate/individual commitment to sustainability goals, (6) Recognition of the productivity benefits of BMPs, (7) Desires to integrate multiple ecosystem services into land management, (8) Cultural and religious legacy, (9) Personal conservation heritage, and (10) Local needs to incorporate effective and successful examples of good natural resources management [2]. Research and development activities play a key part in the refinement and communication of improved BMPs. These projects are also crucial in validating the effectiveness of BMPs. This is especially important where local conditions or operational standards are unique. Best Management Practices function to ensure that forest and agricultural bioenergy programs can be a sustainable part of land management and renewable energy production. There are thousands of BMPs that have been published. Some are common to multiple forest management and farming systems. Others are unique to local environments and management practices and thus not pertinent everywhere.

5. Conclusions

Water and soil are so closely linked that the assessment of positive and negative effects of bioenergy production on water and soils should be part of any integrated analysis considering the environmental, social, and economic dimensions of bioenergy production. Water footprints and other measures have little informative value unless combined with data about resource availability and measures of competing uses at similar spatial and temporal scales. Assessment of the relative positive or negative soil and water effects of bioenergy systems depends largely on whether changes in management of land, water and other resources for bioenergy development alters the state and quality of soil and water [44].

Forest and agricultural bioenergy systems that utilize accepted BMPs should be capable of maintaining soil quality and high-quality water. Excessive removal of plant material from the field or forest may jeopardize soil and water quality. Extended or intensified cultivation of plant annual crops for bioenergy feedstock will produce the same impacts as when the objective of crop cultivation is for food. Cultivation of perennial grasses and woody plants commonly causes less impact on water and soil resources. These production systems can, through well-chosen siting, design, management and system integration help mitigate potential soil and water problems associated with current or past land use. Ultimately, careful land management through the implementation of BMPs will improve soil and water use efficiency.

Advances in water recovery and recycling have the potential to reduce water requirements for conversion processes as well as contribute to the reduction of manufacturing effluents. Feedstock production and conversion stages can, in some cases, be integrated to use resources more effectively and support good land and water management.

The quantity and timing of water withdrawals should be carefully considered in context of water needs, watershed vulnerability, and resilience to disturbance of hydrological cycles. Water scarcity may limit some conventional bioenergy systems in some regions. However, other bioenergy cropping systems may be able to take advantage of currently non-conventional water sources.

Matching bioenergy feedstocks, management practices, and conversion technologies to local conditions and constraints is essential for development of sustainable bioenergy systems. Successful implementation requires investments in the development of suitable plant varieties and conversion systems, systems integration to use resources effectively, and implementation of BMPs in forestry and agriculture.

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Bioelectrochemical Systems for Energy Valorization of Waste Streams

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Abstract

Bioelectrochemical systems (BES) encompass a group of technologies derived from conventional electrochemical systems in which the electrodic reactions are directly or indirectly linked to the metabolic activity of certain types of microorganisms. Although BES have not yet made the leap to the commercial scale, these technologies hold a great potential, as they allow to valorize different liquid and gas waste streams. This chapter is devoted to exploring some of the possibilities that BES offer in the management and valorization of wastes. More specifically, it focuses on analyzing practical aspects of using BES for energy valorization of wastewaters and CO_2-rich streams. Here, it is shown how BES can compete, in terms of energy usage, with conventional wastewater treatment technologies by exploiting the energy content of some of the chemicals present in the wastewater. Moreover, it explores how BES could enable using wastewater treatment plants as load regulation system for electrical grids. It also includes some insights on the capability of BES to recover valuable products such as fertilizers form wastes, a feature that allows this technology to promote energy efficiency in the fertilizers industry, and a sector that demands substantial amounts of energy in our world today. Finally, some of the most relevant scale-up experiences in the field are also covered.

Keywords: bioelectrochemical systems (BES), wastes valorization, wastewater, CO_2, nutrients recovery, energy efficiency

1. Introduction

From a practical point of view, it can be said that bioelectrochemical systems (BES) are conventional electrochemical systems that convert chemical energy into electrical energy (and vice versa) using microbes as catalysts [1]. Although the ability of certain bacteria to generate electrical current was first described more than 100 years ago [2], it was not until the beginning of the present century that this phenomenon started to draw real interest form scientists and engineers. During the last 15 years, the progress made in the fields of bioelectrochemistry and BES has allowed to take the leap from the laboratory to the pilot scale [3, 4] so that commercial development seems to be at hand.

Initial research efforts were focused on exploring the possibilities that BES offered for the treatment and energy valorization (as electric power or hydrogen) of diverse waste streams [5, 6]. To date, the range of applications has broadened dramatically, extending to diverse fields such as desalination [7], bioremediation of contaminated water and soils [8], nutrients recovery [9], or the synthesis of valuable chemicals [10], among many others. Moreover, the versatility and multifaceted nature of BES open the way for applications that lay far beyond bio-based industrial processes. Indeed, when BES are operated in electrolytic mode (see Section 2 in the present chapter), they demand a certain amount of electrical energy, part of which ends up stored in chemical products (hydrogen, methane, etc.). This feature opens the way to using BES as an alternative technology for storing excess electrical power within electrical grids [11]. Thus, BES would offer new storage opportunities, especially in decentralized smart grids, providing a nexus with the waste management systems and offering alternative waste and energy management strategies.

This chapter explores some of the most relevant opportunities that BES offer for energy valorization of waste streams (**Figure 1**). It begins by briefly describing the principles of operation

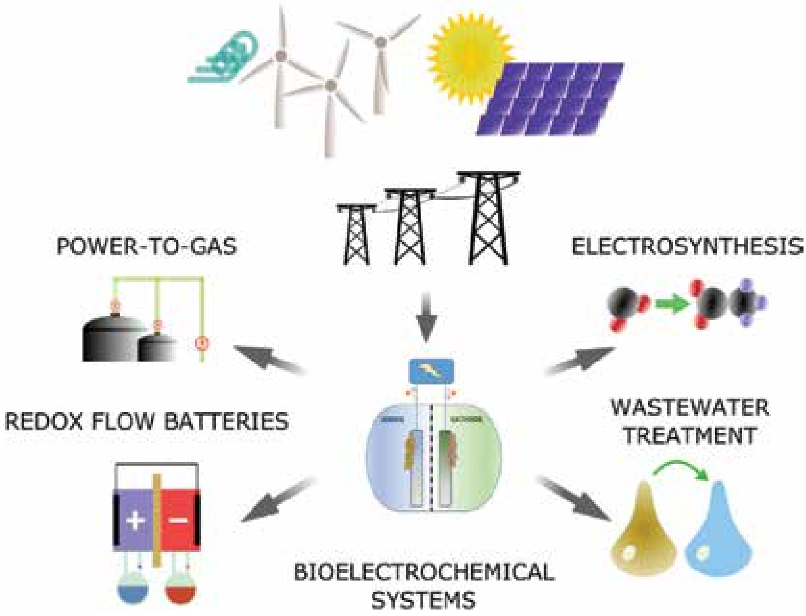

Figure 1. Scope of applications of BES for energy valorization of wastes.

of BES and how they can become useful in energy valorization of wastewaters. It also covers the valorization of CO_2-reach streams paying special attention to fuels production. BES can also bring significant energy savings for the fertilizers' production industries. Given the large amounts of energy that fertilizers producing industries demand around the globe [12, 13], another subsection is devoted to the use of BES for nutrients recovery from wastes. The chapter ends by reviewing the latest pilot scale experiences.

2. Bioelectrochemical systems: What they are?

BES can be understood as electrochemical systems in which at least one of the electrode reactions (anodic and/or cathodic) is biologically catalyzed [14]. They share with traditional electrochemical systems the key feature of being operationally reversible, i.e., they can be run as galvanic cells (the redox reactions are spontaneous) or as electrolytic cells (the redox reactions are non-spontaneous and require a certain amount of electrical energy to proceed). The first BES prototypes operated in galvanic mode were termed as microbial fuel cells (MFC), and when they were operated in electrolytic mode, they were usually referred to as microbial electrolysis cells (MEC). Although this terminology has been somehow transcended as a result the increasing number of BES typologies and architectures that have appeared during the past decade [15], it remains still useful as it mirrors the two basic modes of operation in electrochemical systems. **Figure 2** shows a schematic representation of the principle of operation of BES systems. For more detailed information about the basic principles of BES, the reader is referred to [15].

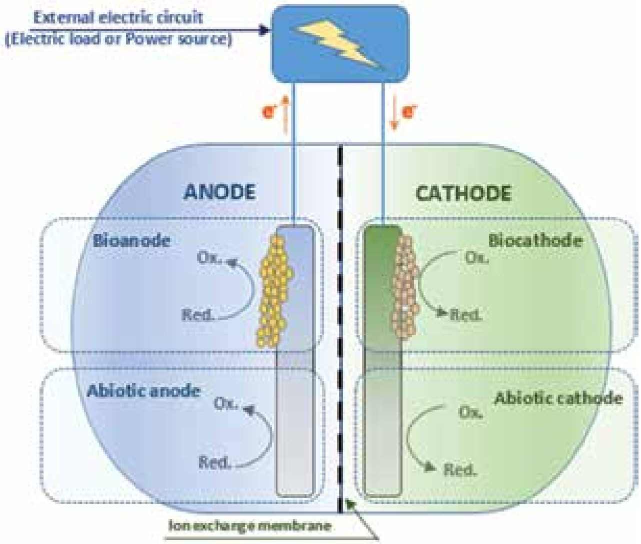

Figure 2. Schematic representation of the principle of operation of a BES. "Ox." stands for oxidized compound, while "red." stands for reduced compound.

3. BES for wastewater valorization

3.1. BES for wastewater treatment and power production

First published studies on MFC and MEC technologies were mainly devoted to further the understanding of how operational parameters (pH, temperature, etc.) affect their performance and to the development of new reactor configurations and new strategies to optimize their figures of merit. Most of these studies were carried out using synthetic media as electrolytes to allow researchers to keep control over substrate composition. Subsequent laboratory tests with real wastewaters served to gain knowledge of the real world potential of MEC and MFC. These studies helped to quantify to which extent reactors performance gets affected by the presence of a real substrate. For instance, MFC fed with actual wastewater produced power densities (normalized to the surface are of the electrodes) in the range of several tens of $mW{\cdot}m^{-2}$ (milliwatts per square meter of electrode) [16], which contrast with the hundreds [17] and even thousands of $mW{\cdot}m^{-2}$ [18] achievable with synthetic effluents. Despite recent advances in electrode materials and reactor configurations [19], power production in MFC has not improved significantly. Issues such as low conductivity and low buffer capacity are often cited as the main factors that explain the observed poor performances [20]. Unquestionably, MEC has to face similar challenges, although economic feasibility criteria seem to be less stringent [21]. For instance, it has been estimated that the target total internal resistance for MEC technology to be cost effective is 80 $m\Omega{\cdot}m^{-2}$, while for MFC this target becomes much more restrictive (40 $m\Omega{\cdot}m^{-2}$) [21]. Moreover, the difference in architecture between a microbial MFC and MEC poses further problems with scaling up. With a pilot scale MFC, aeration to the cathode invites complex issues, as either the cathode cell must be open to the air or there is an added cost of aeration. However with an MEC, the cathode is anaerobic, making the design of a larger system simpler, all of which outlines a more favorable scenario for MEC.

3.2. BES for wastewater treatment and chemical energy storage

Due to its ubiquitousness and the enormous volumes produced globally each year [22], urban wastewater is perhaps the most straightforward waste stream for MECs. The first MEC operated on urban waste water (batch with retention times between 30 and 108 h) offered quite promising results in terms of organic contamination removal (almost 100% removal efficiency), although hydrogen recovery was relatively low (~10% of the theoretical maximum) [23]. In a later study, using urban wastewater as fed as well, it was possible to produce hydrogen at a rate of 0.3 $L_{H2}{\cdot}L^{-1}{}_{R}{\cdot}d^{-1}$ (liter of hydrogen per liter of reactor per day) in a 100 mL (total volume) continuously operated MEC (hydraulic retention times between 3 and 24 h) [24], and energy consumption figures (~1.5 $Wh{\cdot}g{\cdot}COD^{-1}$ (watts-hour per gram of chemical oxygen demand removal)) were similar to those typically found for conventional wastewater technologies [25]. However, when this same MEC design was replicated to a larger scale (3.3 L), hydrogen production declined significantly (0.01 $L_{H2}{\cdot}L^{-1}{}_{R}{\cdot}d^{-1}$) and energy consumption rocketed. In a more recent study performed at a higher scale (130 L) it has been reported energy recoveries of up to 121% with respect to the electrical input [3]. Despite the still important challenges that MECs need to overcome [11], these figures highlight the potential of this technology for exploiting the often untapped energy content of WW [26]. This manifests more clearly if we bring to mind that conventional wastewater treatment plants do not only make use of this potential but also demand large amounts of energy. For example, in Spain, wastewater treatment accounts for approximately 1% of the total energy consumed [27]. BES would enable using the wastewater treatment plants not only as facilities for water contamination removal but also as an electrical regulation system, stocking the surplus of energy in the grid as hydrogen or methane [28]. In this sense, redox flow batteries (RFB), which may become a strategic partner in MEC implantation [29], could offer new possibilities to enhance energy management capabilities of MEC. RFB are electrochemical energy storage devices with a quite interesting feature: they allow to decouple power from energy output [30]. Thus, the reducing power obtained in MEC reactors treating waste streams could be stored in an electrolyte solution that would be easily used for electricity generation or in a subsequent electrochemical process. Well-known RFB, such vanadium systems, presents serious environmental pitfalls for its use in massive energy storage applications [31], but recent approaches, like all-organic RFB [32], could open a wider field. Here, the main candidates are quinone-based molecules [33], which, interestingly, have been previously studied in BES as they may act as intermediates in electron transfer mechanisms [34].

Together with urban wastewater treatment facilities, industrial environments represent another clear niche for potential application of MECs. In general, hydrogen production and energy consumption in MEC improve as the organic concentration in the WW increases. In this sense, industrial wastewater, which usually contains high organics concentration, is an ideal waste effluent for MEC. For instance, by feeding a MEC with the effluent of an ethanol-producing reactor, Lue et al. [35] achieved an impressive hydrogen production rate of ~2 $L_{H2}{\cdot}L^{-1}{}_{R}{\cdot}d^{-1}$ with an electrical energy efficiency of 287%. Still, the use of industrial effluents in MEC may present significant shortcomings. On the one hand, sometimes their composition is not well balanced and may require some nutrient amendment [36], which may not always result in an economically or environmentally feasible approach. On the other hand, dealing with high organic contraction, wastewater in MEC may become an important challenge as it may favor the proliferation of undesired microorganism that could hinder the activity of the electrogenic microorganisms [11].

4. BES for CO_2 valorization

Increasing atmospheric CO_2 concentration is widely seen as the main driving factor behind climate change [37]. CO_2 capture at large emission sources (such as power plants) and subsequent sequestration (mainly in geological or deep sea storage sites) has been put forward as a suitable strategy to limit CO_2 accumulation in the atmosphere [38], although this approach arouses significant public concern [39]. Another alternative more favorable to public opinion and that may help to offset the cost of reducing CO_2 emissions is the use of this gas as a feedstock for industrial processes. In this regard, one among many possibilities is the conversion of CO_2 into valuable chemicals or fuels. The main issue here is that CO_2 is the least energetic (most oxidized) form of carbon, and thus, a substantial amount of energy is required to convert it into useful reduced chemicals. For instance, the Sabatier process that converts CO_2

and H_2 into CH_4 requires high temperature and pressure [40], which usually implies significant energy requirements. Here, BES can provide a suitable alternative through a bioprocess known as microbial electrosynthesis (MES), which requires much milder conditions. MES is a proof-of-concept technology that converts CO_2 into valuable chemicals and fuels within a BES. MES meets the requirements of green chemical technologies as it uses microorganisms as inexpensive and sustainable catalysts, can be operated at ambient conditions, and can be feed with contaminants (CO_2) for environmental remediation [41]. Later, we review some of the target products that can be obtained through MES, paying special attention to alcohols and methane, as these molecules can be easily used as energy carriers in many applications.

Volatile fatty acids (*VFA*). VFA are the most studied group of chemicals synthesized in MES These slightly reduced organic compounds can be produced from CO_2 by a wide variety of microorganisms following different metabolic pathways. Homoacetogens in particular are responsible for acetate production, and recent studies have reported acetic acid production rates above 0.78 $g{\cdot}L^{-1}{\cdot}d^{-1}$, product titers of up to 13.5 $g{\cdot}L^{-1}$, and current-to-acetate conversion efficiencies of 99% [42, 43]. Butyric acid is the second most reported VFA on MES systems. This C4 VFA has mainly been observed as a co-product in acetic acid production systems, although some studies also target this product as main objective [44]. Among the later, production rates of up to 0.16 $g{\cdot}L^{-1}{\cdot}d^{-1}$ and maximum titers of 5.5 $g{\cdot}L^{-1}$ at relatively low conversion efficiencies (40%) have been achieved [45]. Other VFAs such as propionic, isobutyric, or medium chain fatty acids have been found as by-products in lower concentrations in acetic/butyric acid-producing MES systems showing low energy efficiency so far [44].

Alcohols. Bioethanol is a renewable fuel subjected to strong controversy as its production is related to deforestation and to the rising of food prices. MES offers the opportunity of obtaining ethanol from CO_2-rich streams thus avoiding any concern derived from land-use changes. Although ethanol can be produced directly from CO_2, its production from acetate is thermodynamically and energetically more favorable, providing that the undissociated acid exists in a slightly acidic medium [46]. Still, ethanol production through MES is far from becoming a feasible process yet as titers and efficiencies are relatively low (up to 0.5 $g{\cdot}L^{-1}$ and 55%, respectively) [46]. Butanol can also be produced in MES following a similar pattern as in ethanol (butanol begins to appear in butyric acid-producing MES when sufficient reducing agents are present). Butanol has been found as a by-product but not targeted as main product until date, and therefore, the low rates and efficiencies are not representative of its real future potential yet [44]. Other alcohols have been obtained through MES. Arends et al. [47] firstly produced isopropanol in a CO_2-fed continuous MES system, achieving titers up to 0.82 $g{\cdot}L^{-1}$. Soussan et al. [48] reported the possibility of producing glycerol when succinate was present together with CO_2 in the feed. About 100% CO_2-glycerol selectivity was achieved with titers from 6.0 to 9.0 mM.

Methane. Bioelectrochemical power-to-gas. Methane is a valuable energy carrier and a fuel with low environmental impact compared to other fossil fuels. It can be produced from CO_2 through MES by taking advantage of the ability of some microorganisms (e.g., methanogenic archaea) of using a solid surface (cathode) as electron donor. First published experiences reported production rates of 4.5 $L_{CH4}{\cdot}d^{-1}{\cdot}m^{-2}$ and efficiencies up to 80% [49]. More recent studies have succeeded in improving the overall efficiency reaching maximum production rates of 30.3 $L_{CH4}·d^{-1}·m^{-2}$ and efficiencies near 100% [50], yielding high grade gas streams with methane content over 95%, thus opening the opportunity for injection in the natural gas grids.

Another interesting application of these bioelectromethanogenic systems is biogas upgrading. The biogas produced during anaerobic digestion of wastes usually contains large amounts of CO_2 (typically 30–40%), and so to improve its energy value some kind of refinement is usually required [51]. MES can become an alternative to membrane, absorption, or scrubbing units to remove CO_2 from the biogas with the advantage of converting it into more methane. Current studies on using MES for biogas upgrading have been able to keep CO_2 content in the off-biogas permanently below 10%, showing efficiencies over 80% [51, 52]. Although anaerobic digestion and BES have been traditionally seen as two bio-based technologies competing for the same application niches, here we see that both AD and BES can be integrated to overcome some of their inherent limitations.

These studies are revealing that microbial catalyzed reactors are capable of producing a wide spectrum of chemical building blocks, leading to the basis of a renewable chemical platform which might be the future substitute of petroleum-based chemistry. The interaction between distributed electricity grids into delocalized chemical production facilities is extremely attractive, giving a new extension to the biorefineries concept.

5. BES for nutrients recovery from waste streams

Plant macronutrients—mainly nitrogen, phosphorus, and potassium—are indispensable elements for the growth of every living beings. However, when supplied to the soil as chemical fertilizers, they can bring about serious environmental issues (e.g., eutrophication of water bodies and greenhouse gases emissions). World population growth and the ever-increasing demand for agricultural products urge the need for an adequate use of fertilizers to avoid not only their undesired environmental impact but also an eventual depletion of the limited mineral deposits, especially phosphate rock [53]. Furthermore, fertilizers production consumes significant amounts of energy, which brings additional environmental and economic concerns. For instance, 3% of total natural gas production in United States is diverted to the fertilizers industry [12], and fertilizers application in China absorbs 4.4% of China's total primary energy use [13].

Nutrients recovery from wastes can prove to be a feasible strategy to tackle both environmental and energy issues simultaneously. On the one hand, it allows to limit the amount of nitrogen and phosphorus discharged into the environment, and on the other hand, it may help to reduce the energy intensity in fertilizers production. There are several technologies available for nutrients recovery from organic wastes, among which struvite precipitation occupies a preeminent position [54]. BES can also offer the possibility of recovering nutrients from waste streams, and thanks to their ability for harnessing the bioenergy present in the organic matter, they also help to offset the energy usage [55]. Most of the research studies in the literature are mainly focused on the use of nitrogen and phosphorus recovery [56], as these two nutrients are usually found in many organic wastes.

For nitrogen in particular, this element can be concentrated (usually as ammonium) on the catholyte of the BES by migration and diffusion from the anode side. Due to the high pH of the catholyte, ammonium turns into ammonia gas which can be subsequently stripped from the off-gas [57]. The use of BES for nitrogen recovery has been explored using different waste streams, such as swine wastewater, landfill leachate or urine, and different reactor configurations offering encouraging results [58, 59]. Zamora et al. [60] demonstrated that electrical energy required in a pilot scale BES for ammonia recovery is 1.4 $\text{kWh}\cdot\text{kg}_N^{-1}$, which is lower than other electrochemical nitrogen recovery technologies (for instance, 13 $\text{kWh}\cdot\text{kg}_N^{-1}$ is needed to recover nitrogen for digestate using a conventional electrochemical cell [61]). Moreover, some studies have even reported a positive energy balance producing a surplus of 0.96 $\text{kWh}\cdot\text{kg}_N^{-1}$ [62].

BES also represents an ideal technology to precipitate phosphorus, together with ammonium, in the form of struvite thanks to the relatively high pH in the catholyte as mentioned before. Furthermore, BES can be used to mobilize orthophosphate from the iron phosphate contained in digested sewage sludge [63]. Cusick et al. [64] reported a P precipitation efficiency of 85% with an associated energy consumption of 6.5 $\text{kWh}\cdot\text{kg}_P^{-1}$, which was significantly less than that needed by other struvite formation methods based on pH adjustment.

Therefore, the main advantage of using BES for nutrients recovery, compared to other technologies, is that they allow to limit the energy requirements by exploiting the energy content of the organic matter present in a waste [55]. Finally, although the first experiences with pilot plants have already been carried out and give hope to the development of this technology, the use of BES for nutrients recovery still needs optimization of operational parameters [65].

6. Scaling-up BES for energy valorization of waste streams

6.1. The challenges of scaling-up BES

Making the leap from the controlled laboratory scale use of these technologies into pilot scale systems that will inform us of their suitability to real applications is one of the most challenging aspects of research in this area. These challenges are mostly scientific, logistical, and financial in nature; here, we briefly discuss them. When conducting a pilot scale study, even with the best intentions and meticulous planning, it is not always easy to carry out the investigation strictly following the tenants of the scientific method. The use of replicas is a vital way of achieving a scientific method, the resulting reproducibility and reliability of the data collected is standard practice with all laboratory experiments. However, it is rarely considered at pilot scale, where the logistics and expense of operating one reactor are high enough without considering two. Ultimately, therefore most pilot scale studies are not highly scientific, and the information and conclusions we can draw from them are not as strong as those achieved in laboratory-based studies. This is unfortunate, as these studies will actually guide us into the real applications of the technologies developed initially in the laboratory. Achieving the rigor of laboratory testing within a field, a pilot scale study will be essential to take this technology forward.

The logistical problems of setting up a pilot scale project may individually seem like minor and highly surmountable problems, but can combine to have significant detriment to both the financial cost of the project and its outcomes. These problems, and the compromises that need to be made to overcome them, can have significant and long-lasting impacts into the study being undertaken. For example, a reactor planned for startup in the summer months can be delayed into the winter months which in the United Kingdom is a significant decrease in operating temperature, and would result in very slow microbial growth, and potentially a less active and effective biofilm forming. Without a replica reactor started in the summer months, we are unlikely to know the full impact of this on overall reactor performance.

Financial problems can be broadly split into two main areas, finding funding to do this research and then using this funding to build practical systems. BES technologies and the complex microbiology they rely on mean that they do not fit easily into the standard technology readiness levels often used to identify different funding sources. Many of the fundamental elements of BES operate differently at different scales. There is therefore a need to do basic and fundamental science (TR level 1) such as sequencing and understanding microbial dynamics on reactors that are prototypes in an operational environment (TR level 7). Secondly, once funding is in place, different materials need to be sourced which are affordable to use at large scale but will still function in the BES. Thankfully low cost alternatives to most of the materials have now been found, with stainless steel replacing platinum cathodes [66] and cheap battery separators replacing ion exchange membranes [67]. In 2008, these two components were 85% of the costs [20]; however, in recent pilots, they account for less than 2% [67]. The carbon anode material at approximately 100 £·m^{-2} is now the greatest material cost. Furthermore, developing cheaper alternatives to ancillary equipments such as sensors and potentiostats, which are often expensive and not designed to be robust enough for field applications is another challenge.

6.2. A brief summary of the pilot scale studies undertaken in the area of BES

The first large-scale experience with BES was an MFC build and operated by the Advanced Water Management Center at the University of Queensland [68]. The MFC consisted of 12 units with a total volume of approximately 1 m^3. There is scant information about the performance of this plant, although it is known that power production was limited by the low conductivity of the wastewater and biomass proliferation on the cathode [69]. In a much recent work based on a 200 L modular MFC operated in field conditions in a municipal wastewater treatment plant, Ge and He [70] reported more than 75% COD removal rates, accompanied by a power production of 200 mW, which was enough to power part of the ancillary equipment required to operate the plant. Much more complex substrates than urban wastewater have also been used as a feedstock for pilot MFC. In [71], it is reported that a 115 L MFC was able to remove almost all of the biodegradable fraction from swine manure producing about 200–400 mW of power. Moreover, the plant, which consisted of six MFC units, also allowed to remove about 50% of the nitrogen initially present in the manure.

The first large-scale MEC had a working volume of 1000 L, was a continuous flow, and ran a hydraulic retention time (HRT) of 1 day [66]. The system ran for a period 100 days, heated to 31°C, with an average influent of 760 ± 50 mgCOD·L^{-1} (soluble chemical oxygen demand) winery wastewater, along with some acetate supplement. COD reduction averaged 62%; however, hydrogen production was limited as the gas content was 85% methane. The system utilized a single chamber design, which resulted in methanogenesis occurring at the cathode, consuming the hydrogen. Although single chamber designs had been very efficient at the laboratory scale, this study showed that this was not scalable.

Few years later, Heidrich et al. [67, 72] built and operated a continuous flow MEC, which had a volume of 120 L, a HRT of 1 day, and ran for a period of 12 months using raw domestic wastewater (125–4500 mgCOD·L^{-1}) taken directly from the grit channels during pre-treatment. This was in the North East of England and the system was not heated, leading to temperatures ranging from 1 to 20°C. A low COD removal of 30% was reported; however, almost pure hydrogen (100 ± 6.4%) was produced at a rate of 0.015–0.007 $L_{H2}·L^{-1}·d^{-1}$, with a coulombic efficiency (CE) of 41–55%. The cassette design of the electrodes that was developed in this study has seen to be versatile and scalable with its application in other pilots. The study did not reach the required energy recovery to be energy neutral and did not treat the wastewater to EU standards. Inconsistent COD balance, along with a build-up of sludge within the reactor was the cause of the poor performance.

In Ref. [4], a similar cassette electrode design but at two different scales: 0.6 m^2 and 1 m^2 anodes. It ran using settled domestic wastewater (347 mgCOD·L^{-1}), at a real treatment site at ambient temperatures (8.6–15.6°C) for 217 days, with a HRT of 5 h. By decreasing the spacing of the cassettes and increasing the HRT from the Heidrich study, the COD removal was on average 63.5%, and the effluent reached European Urban Wastewater Treatment Directive discharge standards [73]. However, the MEC only produced 0.004 $L_{H2}·L^{-1}·d^{-1}$ with a maximum CE of 27.7%. The problems arose from hydrogen-consuming bacteria entering the cathode compartment and scavenging hydrogen and maintaining a sterile cathode compartment were shown to be vital for successful hydrogen recovery [3].

This MEC used the primary effluent from domestic wastewater, running a 130 L MEC for a period of 5 months, at a temperature range of 18–22°C. Again this research team used the cassette style electrodes as the base for their design, with a HRT of 2 days. Hydrogen was produced at a rate of 0.032 $L_{H2}·L^{-1}·d^{-1}$, which is the highest yet published with a purity of 95%, and consequently, high cathodic gas recovery of 82% and an energy recovery of 121% with respect to the electrical input were achieved. However, COD removal was low at around 25%. This study also treated two types of synthetic wastewater utilizing the same design and discovered that hydrogen production was in fact the highest with real wastewater out of the three carbon sources tested. Although this system is the most successful yet in terms of energy production, problems still occurred, mainly related to application of electric potential and material deterioration.

7. Conclusions

The term bioelectrochemical systems (BES) encompass a group of relatively novel technologies which hold a great potential for energy valorization of a wide variety of waste streams.

Perhaps the clearest niche of application of BES lays in the field of wastewater treatment where this technology could help to improve the energy efficiency of the process by converting the energy content of the organic matter present in the wastewater into either electrical energy or a fuel gas. In fact, most of the pilot scale experiences developed to date have been designed for these purposes. Moreover, operational versatility of BES might bring additional opportunities for wastewater valorization, as they also allow to recover valuable chemicals and nutrients such as ammonium or phosphorus. Here, it is important to highlight that BES can perform this at a reduced energy and economic costs compared to more conventional technologies used in fertilizers industries.

Gaseous CO_2-rich waste streams represent another suitable raw material for BES. Here, BES might provide a means for converting CO_2 into valuable organic chemicals such as methane or short chain fatty acids. This can potentially provide a cost-effective and environmentally friendly method for limiting CO_2 emissions into the atmosphere.

In short, BES can be seen as a group of technologies capable of valorizing a wide range of liquid to gaseous waste streams. In most cases, the operation of BES requires large amounts of electrical energy, most of which ends up stored in chemical energy (methane, hydrogen, etc.) that can be readily converted back into electrical energy when required by using well-established technologies (fuel cells, cogeneration, etc.). This feature would enable BES to operate as electrical regulation system which would bring further commercial opportunities for these technologies.

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Chapter 9

Reverse Flotation

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Additional information is available at the end of the chapter

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Abstract

Reverse flotation of coal can be explained as a process where valuable minerals are depressed, while undesired and unhealthy minerals are floated with the help of some reagents. Nowadays, conventional enrichment method of coal could not achieve removing unhealthy minerals partially from internal structure of coal such as sulfur, Hg, Au, which propagate in air after burning treatment, or heavy metals such as Be, Cr, Ni, As, Cd, Co, Ni, Sb, Se, Pb, Co, Cl, Be, Ba, which involve in water and soil where habitat and human health can directly be influenced from them. In fact, reverse flotation of coal enables to remove these undesired mineral content from coal structure not only in macro size but also in micro size. On the other hand, like undesired minerals, valuable ones like vanadium, germanium, etc. are also taken from coal particles by using the same procedure. Thus, with all these respect, reverse flotation is considered as an alternative and innovative solution for coal beneficiation especially for low rank coal since low rank coal is more compatible for reverse flotation because of being more hydrophilic which means tendency to float is less. Around the world wide, most of the coal reserves belong to low rank coal, so application of reverse flotation is becoming more inevitably common in future.

Keywords: coal, reverse flotation, mineral matter, collector, depressant, frother

1. Introduction

Coal is a type of sedimentary rock, which exists in nature in the form of black-dark gray and brown-black color and consumed as fossil fuel. Besides, coal possesses carbonated plants, and its proportions in terms of weight and volume are more than 50 and 70%, respectively [1].

Raw coal is enriched by different beneficiation methods that are mainly gravity-based separation and flotation. In gravity-based separation, undesired substances, which are not compound of coal, might be reduced but it could not be effective on ingredients being in internal structure of coal. It is dangerous to consume raw coal as fossil fuel for environment due to high amount of sulfur ingredients, because impurities like sulfur produces harmful gases after heating process. Therefore, in order to remove these undesired contents, flotation is applied as an enrichment method.

Flotation, as the name implies, is expressed like separation of substance in compound form by floating process. Floatability of material is crucial aspect for efficiency of flotation. For coal mineral, some of them have natural floatable properties because of its nature, but some others do not possess an inherent floatability because of its internal structure properties [2–4]. The surface texture of coal particle may involve both hydrophobic and hydrophilic zones. Thus, domination of this zones is one of the criteria which decides whether coal is floatable or not [5, 6].

Another criterion for defining floatability of coal particle is moisture content. For example, lignite, which involves 70–80% carbon, has high moisture content and extremely less hydrophobic disposition. The chemical structure of lignite is altering due to elimination of polar groups like hydroxyl and carboxyl groups, and natural moisture content decreases during the transition from lignite to bituminous coal. As a result, coal comes in position of more hydrophobic. Moreover, the content of carbon is in relation with hydrophobicity of coal, too. In the range of 81–89% of carbon content, polar character loses its influence, and coal becomes more hydrophobic. Hydrophobicity of coal reaches its maximum level in 89% of carbon content, and it decreases slightly when the carbon content climbs up from this level. The flotation is directly related with the floatability of particles, so higher carbon content makes conventional flotation process easier [7, 8].

In addition, flotation efficiency is directly related with the properties of the inorganic and organic mineral impurities existed in coals and amount and dispersion of gangue mineral inclusion. It is not possible to remove these finely dispersed impurities inclusion by applying physical methods [9], so flotation should be taken in consideration inevitably in the manner of protecting environment and recovering valuable minerals.

In this respect, flotation is playing significant role in supplying raw materials for various industries. More than 2 billion tons of minerals and fine coals are being processed annually by using flotation in worldwide [10]. For this reason, flotation becomes one of the most important methods for enrichment of minerals and is commonly used in the world [10–13]. At the same time, flotation is utilized for finely-grain-sized coal upgrading [14–18], fly ash decarburization [19], and wastewater treatment [20]. Since coals and ore are liberated in fine grain size, tendency to flotation in mineral processing increases [21].

For environment, sulfur and ash content of coal is too important because heating process leads to propagate harmful gases to the environment. Flotation is one of the effective methods for desulfurization and deashing of raw coal having high ash and sulfur content [22]. Flotation properties depend on the surface texture and other features of particle, so to make particle float or depress in pulp, some different reagents are governed. In conventional flotation, oily collector and frother are used, and these reagents are conditioned in a period of time [23, 24]. In flotation of low rank coal, it is difficult to obtain good result using oily collector due to surface of minerals with low surface hydrophobicity [23]. For this reason, collector consumption is much more in flotation of low rank coal compared with high rank ones [25]. In low rank coal flotation, in order to increase performance, parameters like grain size, pulp density, reagents type and dosage, pulp pH, flotation and time conditioning, and air entrainment rate should be investigated, and [9, 22, 26, 27] most proper condition should be determined with respect to results of them. In addition to conventional flotation method, reverse flotation is also applied on enrichment of minerals.

The reverse flotation was commenced to investigate in 1950s [28, 29]. In following studies after 1950s, different researchers also continued to work on that concept [30–34] and still have been proceeding [4, 25, 27, 35–43]. However, researchers have not understood completely how particles inside the pulp interact with each other, yet because there are many uncertain factors that influence the surface of minerals and coal existing in pulp. Foremost among these factors is that coal possesses different type of elements and behavior of these elements has not been identified; thus, theoretical and experimental verification of interaction between elements is difficult. For that reason, more researches should be performed in that regard. Studies until current time are generally associated with reduction of pyrite and ash. However, recovery of valuable elements in coal should also be taken into consideration in the environmental aspect as well, so the objective of this study is to discuss the benefits of reverse flotation of coal for environment on the behalf of past researches.

2. Process of reverse flotation

2.1. Ash reduction

Ash content is important for both environment and flotation efficiency. Ash content in coal can be eliminated by both physical methods and flotation process, but the presence of ash in internal structure of coal particle could not be removed by physical methods. To be able to remove impurities inside coal particle, reverse flotation is applied on coal. In reverse flotation, tailing is taken as clean coal, and concentrate is accepted as gangue minerals.

Ash content is crucial for coal flotation efficiency. Froth is the key element of determining flotation concentrate, and between concentrate froth and the ash content, there is a strong relation [44].

Ash reduction in reverse flotation of coal subjects have been developed for 30 years by some important researchers. Stonestreet, Pawlik, and Ding have performed intensive studies on ash reduction in reverse coal flotation. Stonestreet and Pawlik prepared their PhD thesis on reverse flotation of coal separately [4, 45] and continued his studies with Franzidis in advance [39–41]. In their experiment, clean coal with 7% ash and silica were mixed as a feed, and quantity of each element was same. From the results of experiments, reverse flotation process, 92% ash reduction was achieved from feed in which ash content was 54%. In depressed coal, ash content was 12%, whereas the recovery of coal is 27%. Results of experiment show that recovery of coal was not good even it was achieved that high ash reduction was obtained

[39]. They continued their experiments to increase the recovery of coal by using three stage addition process, and for same substance, a product of 86% coal throughput involving 12% ash was obtained [40]. Within the matter of improving reverse flotation, they extended their studies and compared the laboratory column cell using synthetic feed mixture consisting coal and quartz. Thus, recovery capacity of coal was much better than in normal flotation [41].

Later, Ding and Laskowski took Stonestreet's studies step further by adding dolomite and calcite as gangue minerals and surveyed the effects of factors on separation. They used dodecyl trimethyl ammonium chloride (DTAC) as a collector whose properties of separation are good when it is used minimum 6 kg/t [2]. After, Ding further continued to study on reverse flotation using DTAC on subbituminous coal, too. DTAC consumption was dramatically descended from 6 to 1.375 kg/t by applying polyacrylamide (PAM) and zero-conditioning time method. Besides, in order to improve selectivity, dextrin was governed, and the addition of tannic acids as a dispersant improved the quality of concentrate. For the feed ash content of 34.6%, the concentrate of 16.7% ash at 50.4% yield was acquired [36].

On the other hand, Patil and Laskowski carried out their studies regarding to enhancing reverse flotation of coal. Patil drew on dodecyl trimethyl ammonium chloride (DTAB) in reverse flotation as collector, but used no depressant, first. Also, zero-conditioning time method was applied in their studies. Zero conditioning was accomplished by adding necessary quantity of DTAB in one step, immediately after system was exposed to the air. The logic behind the zero-conditioning time is that continuity of reverse flotation should not be interrupted in any case. Air bubbles formed from air introducing carried collectors, DTAB, during the flotation process. The entrainment of DTAB carried in air bubble demonstrated that reduction of ash from sub-bituminous coal (LS-26) from 34.7 to 22.9% with gangue yield of 36.8% by using any depressant. In the existence of depressant which was dextrin with 0.5 kg/t, the ash substance of LS-26 was reduced from 34.7 to 16.5% at the clean coal yield 55% [46].

Generally, researchers have been seeking the behavior of ash particles under the participation of different reagents. They mainly focused on low rank coal like lignite due to their hydrophilic properties. Vamvuka also studied on lignite and oxidized coals and used dodecyl amine (DDA) with kerosene in flotation. Ash reduction of 18% with coal recovery of 80% was achieved [47]. Ozturk also proceeded their studies on reverse flotation of Turkish lignite samples involving high ash and sulfur content. They used ionic collector (Aero 3477) and obtained clean coal product of 29.04% ash at a combustible yield of 78.14%, while with non-ionic collector [kerosene], these values altered to 27.04 and 81.19%, respectively [27]. On the other hand, Zhang et al. also worked on reverse flotation, but used different reagents, as a collector dodecyl amine chloride (DAH), as a depressant corn starch, and as a further methyl isobutyl carbinol (MIBC), and observed the effect of particle size in the presence of soluble salt. When the highest reverse flotation performance was achieved, concentrate ash content of 11.30% was obtained with a combustible recovery of 65.29% [43]. Finally, Xia et al. applied reverse flotation on taixi oxidized coals. Dextrin was used as depressant, whereas hexadecyl trimethyl ammonium bromide (HTAB) was oriented as collector [42].

Alternatively, Li studied with sub-bituminous coal involving a significant amount of oxygen which causes to decreasing hydrophobicity. Due to being difficult to upgrade fine fraction in normal flotation, reverse flotation method in which minerals was made hydrophobic by adding collector, whereas coal was made hydrophilic by adding depressants. Li commenced experiments preparing mixture from coarse coal with fine quartz and medium size coal with fine silica. Ash content was dropped around 35% while recovering nearly 85% of combustible material by reverse flotation. The obtained results were much better than that acquired from conventional flotation method. However, when same procedure was applied to fine coal and quartz, separation was not as effective as tests prepared with coarse coal due to influence of hydraulic entrainment [48].

2.2. Sulfur removal

In the early age of 1960s, Eveson was the first person who took attention on reverse flotation by removing shale from bituminous coal. After, reverse flotation had become popular among other researchers, and they started to focus on desulfurization of coal by using this method [30–32, 49].

The presence of sulfur in coal might be found in three forms which can be categorized as organic sulfur, metallic sulfur, and sulfatic sulfur [9, 50–53]. Organic sulfur in coal originates from carbonated plant, while metallic and sulfatic ones' source is inorganic sulfur which exists among mineral compounds. The most common example of metallic sulfur is pyrite and it is called as pyritic sulfur. In addition to pyrite, other minerals may be involved in coal structure such as marcasite, galena, sphalerite, etc. For sulfatic ones, gypsum may be illustrated [54].

The sulfur content is varying by different types of coal, and sulfur content accounts for pyritic and organic sulfur amount in coals. Even coal substances might be extracted from same ore bed, they possess different sulfur content. Pyritic sulfur may represent 20–80% of total sulfur content [38, 50]. Like ash, pyrite particles may also exist in internal structure of coal, so physical methods are becoming nonfunctional in removal of pyrite from coal substance [28]. Flotation was started to be applied to achieve desulfurization as well.

Each type of pyrite mineral shows different floatability properties, and the reason of that was investigated by some important researchers. Feurstenau considered that the cause of that variation is related with the formation of elemental sulfur. Because of being naturally hydrophobic [37, 55, 56], elemental sulfur can conduct with the surface of pyrite, and then, it may behave like a collector for pyrite. Oxidation of pyrite under proper condition forms elemental sulfur, and it is frequently observed in weathered coal, not in fresh coal [57]. Two basic reactions are standing below for expressing elemental sulfur formation from pyrite. These are as follows:

$$2\,Fe^{+3}(aq) + FeS_2 \;=\; 3\,Fe^{+3}(aq) + 2\,S_{(s).} \tag{1}$$

Eq. (1) accounts for formation of elemental sulfur under microbial oxidation of pyrite, i.e. pyrite oxides in moist. To proceed the process of oxidation, acidic environment is necessary because pyrite-oxidizing bacteria can grow under this circumstance [37, 38]; that means, during the pyrite oxidation, iron sulfates, type of salts, constitutes, and these are known as flotation depressant [55]. These depressants can only be dissolved when acidic conditions are satisfied in pulp. On the other hand, unlike formation of sulfate format, if elemental sulfur formation is obtained at the end of oxidation, it is assumed that reaction of coal pyrite is similar to reaction of mineral pyrites, and flotation can be carried out on neutral pH range [37]. Second oxidation reaction may take place with water [58], and it is expressed in the form of;

$$FeS_2 + 3\,H_2O \;=\; Fe\,(OH)_3 + 2\,S^o + 3\,H^+ + 3\,e^- \tag{2}$$

In both cases, if conditions are suitable, substantial quantity of elemental sulfur formation on pyrite sulfur can be observed even the elemental sulfur is normally an intermediate product in a series of reactions that are over with producing sulfate (SO_4^{-2}) [37].

Pyrite has small hydrophobic tendency [55, 59–61] when its surface is unoxidized. With the presence of water, oxidation takes place on surface of pyrite and forms ferric hydroxide, which leads to decreasing hydrophobicity [62–64]. In pH range of 4.5–6.9, oxidation products of pyrite act like strong depressant [60], as it was mentioned before. In order to enhance hydrophobic tendency of pyrite, it is required to add some collector like xanthate [65] since floatability of pyrite intimately depends on pH, and highest floatability might be obtained in acidic pulp [38].

Kawatra performed experiments on fresh coal and 1-year aged coal for different conditions. Fresh coal substances were exposed to different pH levels, and the percentage of froth weight being in directly proportional with floatability of pyrite were investigated. pH levels were defined as 8.3, 7.5, 2.3,2.2, and 2.0, and froth weights were found as 5, 4, 98, 98, and 99%, respectively. On the other hand, same procedure was applied on 1-year aged coal at -15°C, and lowest weight was attained around 37% when pH was almost equal to 6.8, whereas pH was dropped to 2.0, achieved weight dramatically increased, and equal to 92%. Lastly, 1-year aged coal substances were heated up to 100°C and tested in pH level 6.2 and 2.0, and results were 7% and 82%, respectively. From the results, it can be understood that freshly ground mineral pyrite is not readily floatable at neutral pH despite of being highly floatable in acidic pH. On the other hand, pyrite oxidation concludes with sulfate formation, which is not hydrophobic. If necessary conditions might be satisfied for forming elemental sulfur, pyrite can be floated. Also, it is shown that under certain condition, pyrite can be floated at neutral pH, but that is not a normal case. [37]

2.3. Vanadium recovery

Vanadium is strategic metal and has been extensively used in the field of steel and alloy industry. Tensile strength capacity of vanadium is too high, so 80% of vanadium are utilized for alloy steels, whereas remaining portion is applied in chemical industry [66–68].

Vanadium is another element that might be recovered from coal by using reverse flotation. Coal vanadium element can be found in some coal minerals such as illite, muscovite, roscoelite, and kaolin in the form of isomorphism, whereas tantalite and garnet are appeared in the form of absorption [69]. In addition, quartz, calcite, and carbonaceous are found to be main gangues in stone coal [68]. For many studies, flotation has been popular topic for many years, but there are not much more available studies on pre-concentration of vanadium in low-grade coal by the method [70].

Stone coal was exposed to the two stages of flotation processes to recover vanadium microelement. Mineral composition of coal was calcite, barite, quartz, and V-minerals. Reagents were sulfuric acid (pH regulator), oleic acid (Ca minerals collector), sodium silicate (dispersant), sodium fluorosilicate (SFF and depressant), melamine (EA and V minerals collector), dodecyl amine (DDA and V minerals collector), octadecylamine (DC and V minerals collector, terpenic oil (frother)). pH was kept between 7 and 8, and water glass was used as depressant (2000 g/t). Besides, oleic acid was taken 200 g/t as collector [70].

At the end of this study, selective separation of vanadium-bearing minerals can be achieved in pH 3 using melamine (EA). The final vanadium concentrates with V_2O_5 grade of 1.88% and recovery rate of 76.58% are obtained by desliming-flotation process and 72.51% of the raw ore is rejected as tailings [70]. Also, results of other tests demonstrate that grade and recovery of V_2O_5 concentrate are 1.32% and 88.38, respectively, and tailing yield is 38.36%. On the other hand, recovery and grade of carbon mineral which may be used as fossil fuels are 75.10 and 30.08%, respectively [71].

Although vanadium recovery from stone coal is exploring recently by researchers, studies have already been demonstrated how well vanadium is recovered and obtained clean coal simultaneously.

2.4. Effects of rank, mineral, and maceral

Coal quality is determined by many properties, but major factor is coal rank. The rank of coal is identified by the percentage of fixed carbon, moisture (water), volatile matter, and calorific value in British thermal units after sulfur and mineral matter content have been subtracted. Coal types that might be ordered from lowest to the highest rank are lignite, sub-bituminous coal, bituminous coal, and anthracite [72]. Rank directly influences floatability of the coal since chemical structure changes due to elimination of polar groups during coalification process. At the end of this process, carbon content increases, and result in increasing hydrophobicity [73, 74]. Although, rank and floatability are directly proportional, highest hydrophobicity is achieved in bituminous coal, not anthracite, which has highest coal rank, but difference in floatability is not significant between them [75, 76]. Bituminous coals are enough hydrophobic to be floated in further without collector, but in order to improve coal recovery, collector oil is governed [77] even it reduces the coal rank [78].

Moreover, degree of the oxidation of the coal surface is essential for hydrophobicity. It leads coal to act like lower rank coal whose hydrophobicity is lower [4, 79, 80]. However, there are some cases that oxidation increases in the floatability of coal like freshly cleaved coal surfaces. Short-time air exposure may increase hydrophobicity due to drying of the coal surfaces which then becomes more difficult to wet [9].

Coal is composed of many different minerals that influence type of beneficiation method and its applications. These materials cannot be removed from coal totally by using conventional method [81]. Coal has heterogeneous structure, but is mainly formed from inorganic materials such as clay, quartz, sulfides, and sulfates [82, 83]. Mineral content determines the coal grade, and its rate should be less than 50% to be accepted as coal [54]. There are more than

120 minerals involved in coal, and primary ones regarding their degree of presence are quartz, kaolinite, illite, montmorillonite, chlorite (may contain Mn), clays (may also contain Be, Ni, and other trace elements), pyrite (may contain As, Cd, Co, Hg, Ni, Sb, and Se), calcite, and siderite (may contain Mn); not common ones are analcime, apatite, barite, chalcopyrite, clausthalite, crandallite, floricide, gorseksit, goyasite, dolomite, feldspar, galena, marcasite (may contain same elements as pyrite), monazite, rutile, sphalerite (may contain Cd), xenotime, and zircon; and rare ones are chromite, gypsum, gold, gibbsite, rock salt, magnetite, and muscovite [72]. Seventy-six elements of periodic table can be found in coal substance. Some of these are trace elements and their ratios are expressed with ppm. Some trace elements may be concentrated in specific coal bed, which make that bed a valuable resource for those elements such as silver, zinc, or germanium [84]. However, some elements have potential to damage environment like cadmium or selenium if their concentrates are more than trace amounts. Trace elements associated with clays or pyrite are removed from coal by flotation process, and it is significant to dispose all trace element with in the manner of environment and recovery of valuable elements. Nevertheless, except for gypsum, the various forms of ash and germanium, recovered minerals have not been used commonly [72].

In addition to rank and mineral matter, maceral also affects the flotation of coal since coal hydrocarbon structure and hydrophobicity are influenced by maceral content [78, 85]. The macerals consist of lithotypes, and their proportions vary. The properties of lithotypes also differ from each other. Macerals are classified into groups according to dominant components, which are vitrine, inertinite, or liptinite, and has different hydrophobicity. For example, the lithotype fusain involving inertinite group macerals is generally the least floatable, whereas vitrian involving vitrinite group macerals is the most floatable [75]. Studies associated with maceral recovery proved that it is possible to regain good volume macerals without much loss of combustible value [83]. The studies on floatability of coal macerals were appeared at the beginning of 1950 by Horsley [8] and Sun [86]. According to Burdon, maceral content changed with increasing time flotation [87]. Even in same flotation cell, maceral content could vary when samples were taken from different place of it [3] because the macerals are the basic microscopic, physically distinct, and chemically different constituents of the carbonaceous matter in coal, which originate from material deposited in the primeval swamps [83]. Due to variance in maceral content, it is essential to define coal nature and response each maceral during the flotation. Based on maceral content in clean coal, the use of coal can be optimized. For example, high liptinite content increases the calorific value, whereas high inertinite content in concentrate stimulates increase in fixed carbon [88].

Rank, mineral content and macerals are influencing the flotation performance and type because these are essential parameters for floatability of coal. Reverse flotation can be optimized for low rank coal because low rank coal can be suppressed more easily since hydrophobicity of low rank coals are more less due to its polar structures. In order to recover valuable minerals and remove hazardous minerals at the same time, reverse flotation is again proper way because mineral content of low rank coal is more compared to high rank coal, so minerals might be floated without taking much more effort. Lastly, macerals can be divided into some groups according to compounds content as it was mentioned before. Coal with lowest floatable maceral, fusain, may be upgraded by using reverse flotation, too.

2.5. Effects of pH

The pH has great importance in flotation because pH of liquid phase influences the surface characteristics and behavior of mineral and induces minerals to absorb all types of reagents on the surface. Response of reagents to the pH is essential for flotation, and there are no standard pH values for particular minerals in flotation. Instead, it is generally expressed with range for flotation of specific minerals, and it may differ according to participating reagents. For this reason, this may become complicated and needed to perform sensitive when highly selective products are required. Like coal reverse flotation, effects of hydroxide ions (OH^-) and hydrogen ions (H^+) ions are not only important for floating mineral matter but also important for suppressing coal [89]. Mineral surface can be altered with adjusting these ions in pulp. Minerals in pulp can be charged positively or negatively by arranging pH regarding the isoelectric point (IEP). When the pH is higher than IEP, minerals charge negatively, on the contrary, opposite actions will take place in mineral charging. Zeta potential is related with absolute changing in pH with respect to IEP, so it increases slowly [90, 91].

The pH plays important role in pyrite removal, which is hazardous mineral for environment. Mineral pyrite and coal pyrite act different. Inherently, mineral pyrite is floatable, and it loses its floatability when pH is greater than 5.0. When the pH range is between 5 and 9, the recovery of mineral pyrite is not noticeable even neutral oil collectors are utilized to render mineral pyrite floatable. Although same fashion is used for coal pyrite, it does not act as mineral pyrites. In the pH range of 2.2–8.8, coal pyrite can be recovered 31–43%, whereas mineral matter pyrite can be achieved to regain 99% over the same pH range. Kawatra carried out microscopic examination of coal pyrite flotation and resulted in floated materials that were coal and locked coal/pyrite particles. Therefore, it is assumed that coal pyrite was floated due to attachment to coal [38]. Chander and Aplan performed studies to prove that pyrite is inherently less floatable due to exposed oxidation during purifying from coal which may result in destroying floatability of pyrite [34]. The studies show that coal pyrite may be floated due to locked or entrained particles [38]. Some experiments were handled by Kawatra to examine the effects of pH with using different reagents. In the first experiment, the pulp pH was arranged lower than 4.0, and fuel oil was used as collector for mineral pyrite. Flotation could be achieved with the range of that pH, but native floatability was entirely lost with higher pH values. In second trial, coal pyrite was tried to be floated. However, coal pyrite may behave like mineral pyrite, and it was not recovered at neutral pH range [38].

The effects of surface and solution chemistry of Fe(II) and Fe (III) ions on the flotation of both mineral and coal pyrite with xanthate were investigated based on flotation output, zeta point measurements, and thermodynamic calculations. The results showed that existence of ferrous and ferric ions induced pyrite depress in pH range 6–9.5. Coal pyrite was recognized non-floatable above pH 6 due to large number of ferrous ions resulted from pyrite oxidation. Moreover, thermodynamic calculations demonstrated that formation of ferric hydroxyl xanthate leads to reducing floatability of pyrite when the pH is greater than 6.0 [92].

On the other hand, some additional experiments have been performed for different types of minerals existing in coal structure. As it is well known that materials vary between each other with respect to their properties. Like pyrite, ash also can be recovered by reverse flotation along the different pH ranges. Stonestreet performed studies on ash reduction by applying reverse flotation method on quartz coal mixtures with same amount. The result of their studies showed that maximum ash reduction was succeeded using talk water whose pH was equal to 7.6 [4]. After, Pawlik also touched upon ash reduction with different coal substances. Sub-bituminous, bituminous, and oxidized bituminous coal were objective of reverse flotation with different pH ranges. At first, bituminous coal were exposed to different pH ranges, and optimal results for normal and oxidized coal differed. For normal bituminous coal, the flotation yield went into decline for higher pH values than 9.5. However, sharp decrease was observed when pH level becomes higher than 4.0 for oxidized bituminous coal sample. Besides, different tests were performed for sub-bituminous coal/silica mixtures, and for these tests, optimum pH range was determined between 8.3 and 8.6 [25]. Moreover, Ozturk mainly focused on ash reduction by reverse flotation of lignite, and they achieved maximum level of reduction at neutral pH range around 8 [27]. Same with Ozturk, Zhang also implemented reverse flotation on lignite sample at neutral pH level [73]. Lastly, sub-bituminous coal/quartz mixture with ratio 7:3 was subjected to the test, and all tests were done at neutral pH level [48]. Some additional examples are given from different pH ranges to represent bad results. For example, the low ash content of concentrate was obtained around 10.5 pH value due to optimum flotation of calcite and dolomite around this pH [93].

As well as ash and pyrite, some other valuable minerals can also be regained by reverse flotation throughout different pH levels. Ding worked on sub-bituminous coal sample with 48.5% ash content and gangue minerals such as calcite dolomite and silica with the ratio of 7:1:1:1, respectively. These gangue minerals were intended to be floated. In first study, when pH was 10.4, these gangue minerals can be floated [35], whereas in second test, zero-time conditioning was also taken into consideration, and maximum yield was achieved at the 7.5–8.4 pH range [36]. Wang also tried to float calcite as well as vanadium, which has great value in industry. For calcite, pH level varied between 7 and 8, while it was 3.0 for vanadium [70].

Therefore, importance of pH is clearly explained by studies, and more research should be carried out to take a step further in reverse flotation.

2.6. Effects of particle size

The most important criteria of mineral processing is associated to size of liberated mineral particle. The performance of flotation process depends on the degree of liberation of mineral in fine fraction. For this reason, flotation is applied to minerals that are intended to recover or remove from coal. Coal has a complex structure and possesses various minerals. Although the particle size of coal is generally less than 0.5 mm, liberation may not be achieved in that fraction size, so grinding may become inevitably for well separation. Hence, it is compulsory to apply flotation on coal due to liberation in fine fraction phase. However, finer fraction does not always mean that every parameter related with flotation is obtained in well range. There is a trade of between fraction size and performance of flotation. In **Table 1**, some studies with different coal type associated with various fraction size are demonstrated.

Zhang et al. studied on lignite which possessed 42.34% ash content by applying reverse flotation. Recovery amount and flotation performance can differ with respect to particle size.

Coal type	Particle size (micron)	Floated minerals	Reference
Sub-bituminous coal/quartz	150–200 (coarse coal), 74–120 (medium size coal)	Mineral matter	[50]
	−38 (fine coal), −200 (raw coal)		
	−56 (fine silica), −200 (coarse silica)		
Lignite with 42.34% ash content	−425, 250–425, 150–250, 150–74, 74–45, −45	Ash	[43]
Lignite	100 (86% of material finer mineral than 100 micron)	Ash	[27]
Low grade stone coal (mass fraction)	−38, 38–50, 50–74, 74–154, 154–300, +300	Carbon, vanadium	[71]
Low grade stone coal	−38, 38–50, 50–74, 74–154, 154–600, 600–1500, +1500	Carbon, vanadium	[70]
Taixi oxidized coal	250–500, 250–125, 125–74, −74	Mineral matter	[42]
Lignite	+300, 300–75, −75	Ash	[47]

Table 1. Particle size of minerals participating into the reverse flotation.

Maximum performance was obtained for −74-micron fraction size with the combustible recovery of 65.29% and ash content of 11.30% after 20 minutes flotation. However, maximum flotation rate constant was achieved in 150–250-micron range, and the maximum reverse flotation index efficiency was attained for −425 microns. Hence, combustible recovery increased with increasing size fraction but meanwhile the concentrate ash content also increased particularly for finer particle sizes [73]. For finer fraction, slime problem appears. Because of that reason, there must be performed detailed studies for finer fraction flotation in order to obtain optimum results.

2.7. Reagents (collectors, depressants, and frothers)

The purpose of using reagents is to change the surface properties of minerals to adjust which material is floated and depressed. In this concept, regulator reagents (pH adjustor, activator, depressants, and dispersants) are entrained into flotation process to improve quality of selectivity and separation. In **Table 2**, reagents are demonstrated in three groups: depressants, collectors, and frothers. Most of reverse flotation experiments are listed, and for each test, available used reagents are indicated (**Table 3**).

Collectors are the reagents, which cause to arranging hydrophobicity of material. Collectors can be observed into two main topics that are ionic and non-ionic collectors. Non-ionic collectors are organic compounds formed from hydrocarbon chains having no neutral and polar groups, whereas ionic collectors are divided into two groups, anionic and cationic. The surface properties of minerals determine the reagents selections, and after necessary conditioning is done, flotation process starts. Some of the preferred collectors in reverse flotation are DTAB, HTAB, DTAC, and so on. On the other hand, PAM and ferric silicate were governed besides collector in order to increase activation of them. On the other hand,

Coal type	Depressant	Collector	Frother	Reference
Bituminous coal	Inorganic oxidants	Octylamine, CTAC, FAA, CTAB, CDBAC, LPC	MIBC	[29]
Subbituminous coal	Not used	DTAB	MIBC*	[45]
Bituminous & sub-bituminous coal	Dextrin	DTAB, PAM	DTAB	[94]
Bituminous & sub-bituminous coal	Dextrin	DTAB	MIBC	[46]
Sub-bituminous coal	Dextrin	DTAC	not used	[36]
Sub-bituminous coal	Dextrin	Lilaflot D817M	MIBC	[48]
Clean coal and silica mixture	Humic acids (HA)	DTAB	MIBC*	[45]
Calcite, dolomite, silica, and raw coal	Dextrin	DTAC	Not used	[35]
Quartz and clean cooking coal mixture		HTAB, HPYC		[39, 40]
Taixi oxidized coal	Dextrin	HTAB	–	[42, 95]
Quartz and clean cooking coal mixture		HPYB		[39]
Lignite coal	Not used	Aero-3477 (anionic collector), kerosene	Pine oil	[27]
Mineral pyrite	Not used	Fuel oil	MIBC	[37]
Pittsburgh coal	Not used	Fuel oil	Dowfroth 200	[37]
Mineral pyrite, coal	Not used	Fuel oil	Dowfroth 200	[48]
Quartz and clean cooking coal mixture	Dextrin	DTAB	MIBC	[39, 40]
Lignite coal	Not used	(Cationic; DDA, TTAB)	MIBC	[47]
		Anionic; SDS, non-ionic (2-ethyhexanol)/kerosene		
Lignite coal	Corn starch	DAH	MIBC	[43]
Low grade stone coal	Sodium silicate	oleic acid, EA, DDA, DC, Mixed Alimine	Terpenic oil	[70, 71]
Silica and raw coal mixture	Humic acids (HA)	DTAB	MIBC*	[25]

Table 2. Use of reagents in reverse flotation.

depressants are the reagents which are added to the pulp to make mineral surface more hydrophobic. As depressants, commonly used reagents in coal reverse flotation are dextrin, humic acids, and corn starch. Frothers are utilized for forming small size bubbles and durable forth which can bear floated minerals without getting any damage during transportation process. In reverse flotation, most common reagents are MIBC, and pine oil, terpenic oil, and

- MIBC* indicates that it was not used for all experiments
- TTAB, Myristyl trimethyl ammonium bromide
- SDS, Sodium dodecyl sulfate
- EA, Melamine
- DAH, Dodecylamine hydrochloride
- DC, Octadecyl amine
- FAA, Fatty amine acetates
- LPC, Lauryl pyridinium chloride
- DDA, Dodecyl amine
- HPYC, Hexadecyl pyridinium chloride
- HPYB, Hexadecyl pyridinium bromide
- CTAC, Cetyltrimethylammonium chloride
- CTAB, Cetyltrimethylammonium bromide
- CDBAC, Cetyl dimethyl benzyl ammonium chloride
- Dowfroth 200, A polypropylene glycol methyl ether

Table 3. Abbreviations.

Dowfroth 200 follows it. On the other hand, the use of frothers is not compulsory for reverse flotation because some collectors possess foaming agents.

Alternatively, Yi et al., stated that waste cooking oil (WCO) can be converted into a bio-flotation agent (BFA), which can be replaced with diesel improves a new coal flotation agent with Zr-SBA-15 catalyst. Pilot program data demonstrated that WCO to BFA brings saving energy by 13%, and CO$_2$ emission by 76% as well as production cost when compared with petro-diesel use [96]. As a new trend, environmental aspects should be considered so that less harmful collectors should be employed within the manner of reducing the damage to environment, and in this respect, more studies should be handled to overcome environmental issues.

2.8. Conclusion

Flotation was developing at the end of 1800s, and reverse flotation was first tried in 1960s. Although not much researcher paid attention on reverse flotation issue, they contributed to literature significantly through past 50 years. With respect to these results, it is inevitable to reach success by reverse flotation.

SO$_2$ gases are the main triggering factor of acid rains due to propagating toxic gases after burning treatment. Sulfur gases may be found in coal in the form of organic and mineral sulfur (pyrite, marcasite, galena, and sphalerite) and sulfate (Gypsum—$CaSO_4 \cdot 2H_2O$ and Barite—$BaSO_4$). In order to restrain environment and habitat from unhealthy gases, before burning treatment of coal, they should be removed from coal. Besides, Hg and U spread to the air by burning treatment. On the other hand, minerals like Be, Cr, Ni, As, Cd, Co, Ni, Sb, Se, Pb, Co, Cl, Be, Ba, etc. may involve in water and vegetation cover and lead to great damage for habitat. These heavy minerals are also dangerous for human body because human body could not get rid of these minerals easily and cause to irreversible damages. Because of that, these minerals should be removed from coal in prior to burning treatment. Another issue about coal is about eliminating the harmful effects of CO$_2$, which causes greenhouse effects. To achieve this, beech trees which has great potential of consuming CO$_2$ gases in photosynthesis process and the habitat of artificial trees should be constituted especially in the area where coal is being consumed as a main energy source.

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Reused Lithium-Ion Battery Applied in Water Treatment Plants

Yi-Hsien Chiang and Wu-Yang Sean

Additional information is available at the end of the chapter

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Abstract

For stabilizing renewable energies and shaving peak power at noon, both the energy consumption and potential renewable energies in Dihua waste water treatment plant (WWTP) in Taiwan are analyzed. Under the consideration of environment, cost, and performance, automotive reused lithium-ion battery (RLIB) is employed. Two typical automotive lithium-ion batteries are used in this study after the selection of suitable battery cells. In particular, one simple, converterless energy management system (EMS) is developed and integrated in new RLIB packs. The control strategy between RLIB and an additional physical battery is adjusted by simulation. An online estimation of RLIB's internal resistance and open-circuit voltage monitoring scheme is applied in EMS to ensure the safety of RLIB. The bench test and rough economical estimation reveal that EMS shows great potential in elongating life cycle and possibly benefits from feed-in tariff and peak shift of electricity charges.

Keywords: reused lithium-ion battery (RLIB), wastewater treatment plant (WWTP), energy management system (EMS), peak shift, feed-in tariff (FIT)

1. Introduction

The Dihua wastewater treatment plant (WWTP) is between the Tamsui and Keelung Rivers in Taipei. It treats sewage from Taipei City's household connections and interception stations. The plant, which has a capacity of 500,000 m^3/day, is the largest secondary treatment plant in Taiwan. Water Resources Agency (WRA) in Taiwan recently launched several projects to promote energy self-efficient WWTPs. Their action plan is to employ green energy sources in WWTP by collocating with efficient new water treatment processes. Green energy sources refer to well-known renewable energy sources (e.g., biomass, wind energy, solar energy, hydropower, and local waste heat).

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Some projects in the world originated from the concept of the energy–water nexus, which is the coupling of energy, water, the environment including climate change, and food supply [1–9]. Studies conducted on WWTP and in collaboration with local governments and major organizations provide solid evidence of unit electricity for wastewater treatment or neutral energy. Electricity from renewable energy resources, such as wind or solar power, may be used to partially or completely replace electricity from the grid. Moreover, novel wastewater treatment processes have been employed in WWTPs to reduce the energy requirements per unit volume of treated wastewater in comparison with cases that depend on electricity only from renewable energy resources [10–15]. Some researchers illustrated that energy cannot be gained at all from aerobic digestion or organic substances at WWTPs and sludge treatment plants. The specific energy demand at these plants is still high, and too much energy is needed for far-reaching aerobic degradation of organic substances. However, biogas from anaerobic treatment from WWTPs or waste management may become a suitable way of improving energy efficiency. For alternative sanitation concepts, sewage and food waste management, or other environmental assessments of urban water systems [16, 17], life cycle assessments should be conducted to explore plant energy balance. Besides renewable energy, one potential candidate for compensating the consumption at WWTPs is wastewater heat recovery. Case studies show that technologies for heat recovery from wastewater also have been successfully implemented. However, heat recovery may harm the wastewater treatment process and reduce the performance of WWTPs [18–26].

Lithium-ion batteries contain precious metals such as lithium, cobalt, or manganese; therefore, recycling and recuperation of these batteries are highly advantageous. However, these processes use high levels of electricity in traditionally chemical methods [27–32]. Lithium-ion batteries are suitable as ancillary services or for supporting large-scale solar and wind integration in existing power systems by providing grid stabilization or frequency regulation [50]. Lithium-ion batteries are also classified as dangerous waste. If they are not properly treated, then they will damage the environment and cause harm to humans and the environment. By contrast, abundant electrical capacity remains in discarded lithium-ion batteries. Following an intensive review on advanced smart metering and communication infrastructures, a strategy for integrating electric vehicles (EVs) into the electric grid is presented [51]. Under the vehicle-to-grid phenomenon, the deployment of EV batteries in the energy market can compensate for fluctuations of the electric grid. A previous study [52] presented the optimization of electrical energy storage systems and improved control strategies based on hybrid power source and series.

To achieve energy self-efficient WWTPs, we consider several ways of ensuring positive energy balance of wastewater treatment such as renewable energies. In this study, automotive reused lithium-ion battery (RLIB) is used to accumulate electricity at night to shave peak power in the grid at noon as a prior phase before chemical separation of the RLIB pack. In general, RLIB packs might decay rapidly after being discarded, and the energy management system (EMS) is developed to address this issue. The performance of depth of discharge (DoD), which indicates the life cycle, is used to determine the effectiveness of EMS in bench test. Besides, an online scheme of estimating life cycle sensitized parameters is embedded in EMS for safety and performance guarantee.

2. Analysis of energy consumption and potential renewable energies

After dividing a portion of effluent from the Dihua Sewage Pumping Station in Taipei, sewage enters the Dihua WWTP at an average of 434,349 m^3/day. It then passes through fine bar screens to remove coarse materials. It flows into primary clarifiers to remove the greater part of the suspended solids and a small portion of the organic matter in the sewage. Aeration basins and secondary clarifiers are used to remove organic matter in the sewage. The effluent from the secondary clarifiers is disinfected with sodium hypochlorite to remove pathogens before discharge into the Tamsui River. After sand filtration, 10,000 cubic meters per day of effluent become reused water for the plant. Night solids, combined with primary sludge and secondary sludge, is thickened, anaerobically digested, and dewatered to become sludge cake. It is then disposed in a landfill site or used as fertilizer for inedible vegetation by any organization that requests it. The energy consumption is listed in **Table 1**.

In the Dihua plant, the entire water treatment process consumes 120,526 kWh of electricity a day. Approximately 0.28kWh/m^3 is required for wastewater treatment. This value is much lower than UNESCO's report (2014) of 0.62–0.87 kWh/m^3 excluding pumping to the treatment site and equipment efficiency. The average quantity of energy used varies considerably depending on the level of treatment, type of treatment, and size of plant, but it approximately doubles from primary to secondary and doubles again to tertiary levels of treatment (US EPA Office of Water 2013).

In Dihua's case, the outcome of biomass occupies 55.69% total unstable renewable energy as listed in **Figures 1** and **2**. Twenty percent of total area is assumed to be installed solar panel, and the reliable electricity capacity of 943.8 kW is obtained. Hydropower and wind power are not dominant energy resources in this plant.

Process	**(%)**	**Energy consumption (kWh/day)**	**Energy demand unit volume (kWh/m^3)**
Aerobic digestion	25.47	30697.67	0.0706
Sludge treatment	6.15	7416.02	—
Secondary clarifier	5.40	6503.03	0.0149
Wastewater pumping	5.12	6167.67	—
Solid dewatering	3.28	3954.15	—
Lighting and building	3.22	3875.41	—
Disinfection	2.28	2750.31	0.0063
Grit	0.67	807.31	0.0018
Primary clarifier	0.47	571.32	0.0013
Anaerobic digester	1.09	1318.28	—
Aeration	46.85	56465.37	0.13
Total	100	120526.57	—

Table 1. Usage of energy consumption in Dihua WWTP.

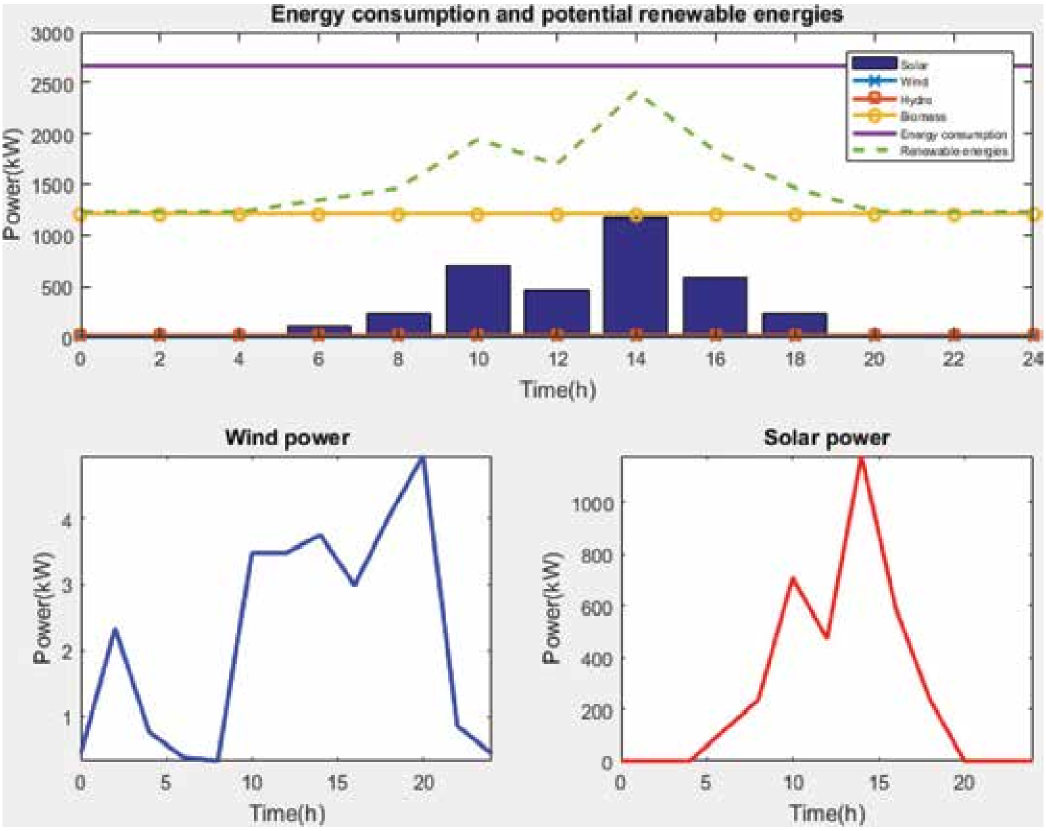


Figure 1. Unsteady renewable energies in Dihua WWTP.

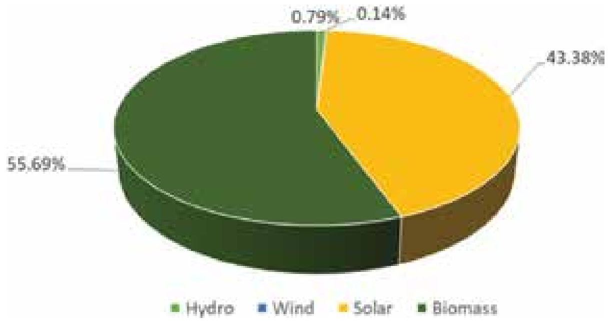


Figure 2. Potential renewable energies in Dihua WWTP.

3. Motivation of using RLIB

Demand for urban vehicles focusing on sustainable transportation has prompted a substantial trend towards automotive electrification such as hybrids and EVs. With more than 70% of EVs likely to be introduced in 2015 with Li-ion based battery chemistry, the recycling of Li-ion has

Figure 3. Reused Lithium-ion battery used in pure electric vehicles (left: $LiFePO_4$, right: $LiMnNiCoO_2$).

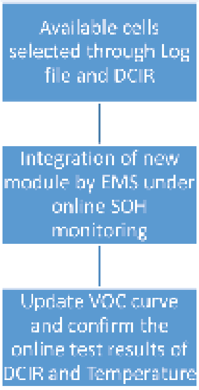


Figure 4. Flowchart of RLIB.

Figure 5. About 8 hectares huge space in the second deck of aeration tank in Dihua plant.

become a crucial topic in the automotive industry. When the battery packs in a lithium-ion-powered vehicle are deemed too worn out for driving, they still have up to 80% of their capacity left. Before they ever arrive in a recycling center, these batteries are used to prop up the grid, especially alongside energy sources that may not be quite as steady, such as wind or solar power

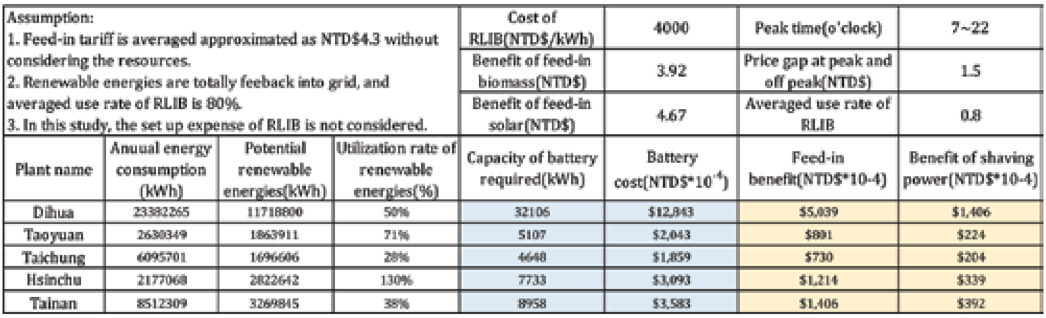
(**Figure 2**). Furthermore, the cost of RLIB is roughly cheaper than 1/3 of a new battery. This merit enhances strong competition compared with other cheap flow batteries or NAS batteries.

For instance, two packs of RLIBs are shown in **Figure 3**. Both of them are originally applied in pure EVs. After working for several years, they are used as experimental targets before cycling and recuperation by chemical method. In this study, two different types of packs are selected. The flowchart in **Figure 4** shows that suitable cells are activated and selected based on log file and DC internal resistance, and each new module is assembled with EMS. Subsequently, the module is installed in a test bench to update voltage of open circuit (VOC). In addition to establishing water, energy, and reusing nexus in urban areas, the Dihua WWTP is chosen for its large area of 8 hectares. Thus, an extensive enclosed space is available for placing RLIB between the aeration tank and green park in the ground (**Figure 5**).

4. Benefit of energy management in WWTP

Reducing variability in renewable energy is crucial in managing the peaks in WWTP. As a result, this strategy is dispensable for employing energy storage systems charging during off peak times and injecting energy into smart grids during peak times. Benefits can be estimated from the low price at night, cost of basic contract fee of electricity, and effect of frequency regulation.

Results of the economic benefit assessment are shown in **Table 2**. We assume that renewable energy's purchase price is 0.143 USD. Renewable energy is assumed to be fully fed back to the grid. About 80% of the total RLIB is used as night storage, and the cost of RLIB is 133USD unit kWh. In the case of Dihua plant, the calculation of RLIB demand is 32,106 kWh, which is roughly equivalent to 3200 pure EV battery pack. This value is also about 1/20 of the total number of domestic sales of EVs from 2011 to 2016 in Taiwan. The initial cost of RLIB packs is 4.3 million USD. However, only the sales of renewable energy power into the grid based on feed-in tariff (FIT) are 1.68 million USD. The annual electricity rate difference at noon and night is 140.6 million NTD, and the annual income at noon and night is 4.69 million USD. Therefore, the plant can break even in 2 years and continue to profit each year without considering the installation fee. Other plants also show similar profitable results such as Dihua plant in **Table 2**.



<table>
<tr><td colspan="4" rowspan="3">Assumption:
1. Feed-in tariff is averaged approximated as NTD$4.3 without considering the resources.
2. Renewable energies are totally feeback into grid, and averaged use rate of RLIB is 80%.
3. In this study, the set up expense of RLIB is not considered.</td><td>Cost of RLIB(NTD$/kWh)</td><td>4000</td><td>Peak time(o'clock)</td><td>7~22</td></tr>
<tr><td>Benefit of feed-in biomass(NTD$)</td><td>3.92</td><td>Price gap at peak and off peak(NTD$)</td><td>1.5</td></tr>
<tr><td>Benefit of feed-in solar(NTD$)</td><td>4.67</td><td>Averaged use rate of RLIB</td><td>0.8</td></tr>
<tr><td>Plant name</td><td>Anuual energy consumption (kWh)</td><td>Potential renewable energies(kWh)</td><td>Utilization rate of renewable energies(%)</td><td>Capacity of battery required(kWh)</td><td>Battery cost(NTD$*$10^{-4}$)</td><td>Feed-in benefit(NTD$*10-4)</td><td>Benefit of shaving power(NTD$*10-4)</td></tr>
<tr><td>Dihua</td><td>23382265</td><td>11718800</td><td>50%</td><td>32106</td><td>$12,843</td><td>$5,039</td><td>$1,406</td></tr>
<tr><td>Taoyuan</td><td>2630349</td><td>1863911</td><td>71%</td><td>5107</td><td>$2,043</td><td>$801</td><td>$224</td></tr>
<tr><td>Taichung</td><td>6095701</td><td>1696606</td><td>28%</td><td>4648</td><td>$1,859</td><td>$730</td><td>$204</td></tr>
<tr><td>Hsinchu</td><td>2177068</td><td>2822642</td><td>130%</td><td>7733</td><td>$3,093</td><td>$1,214</td><td>$339</td></tr>
<tr><td>Tainan</td><td>8512309</td><td>3269845</td><td>38%</td><td>8958</td><td>$3,583</td><td>$1,406</td><td>$392</td></tr>
</table>

Table 2. Benefit assessment of 5 WWTPs applying RLIB (NTD; 30NTD = 1USD).

5. Development of EMS

To reduce the peak current in LIB pack, a physical battery is employed in LIB effectively, but range extension is still limited in the case study [33]. The effect of life cycle extension is discussed [34] by the transient supply of physical battery. Given the traditional large DC/DC converter in EMS, a small prototype of DC-DC and simple circuit may be proposed to isolate the battery pack and not harvest energy from random peak power [35, 36]. The scenarios of usage cover the regenerative power supply and charging/discharging between individual and physical batteries. Some studies have focused on the design of levering DC-DC converter [37, 38], but several researchers have introduced a converterless circuit in EVs based on a DC inverter [39, 40]. The literature implies the possibility of EMS with high efficiency and low cost. Specific control strategies including neutral networks are illustrated in [40–42]. Economic analysis shows that the high price of LIB leads to superior benefits in elongating life cycle. Real-time simulators are a powerful platform before on-board tests [42]. In [43], a simple circuit of elongating life cycle life was reported. Without a complex DC-DC converter, only duty control using a suitable physical battery can narrow DoD of LIB and elongate the life cycle of batteries [44–48]. **Figure 6** shows the relationship between DoD and life cycle. None of the lines in **Figure 8** are linear, thereby indicating that DoD plays a major role in gaining life cycle.

Figure 7 shows a simple, converterless parallel circuit. EMS can achieve active control by switching the discharging ratio between LIB and auxiliary physical battery at unit time. The architecture of EMS is shown in **Figure 8**. It is modified from battery management system. EMS is disposed as an interface among RLIB, auxiliary physical battery (ultracapacitor, UC), and systematic grid. The control strategy aims to keep the switch periodically close and open by a predetermined duty cycle, namely, the sharing ratio of RLIB's loading controlled by EMS. In detail, EMS generates a PWM (pulse width modulation) signal to control the on/off time of the lower arm of the switch module.

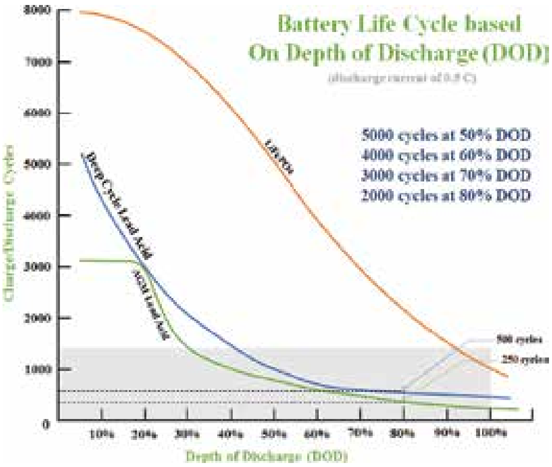


Figure 6. Relationship between DoD and charge/discharge cycles (life cycles) modified from [49].

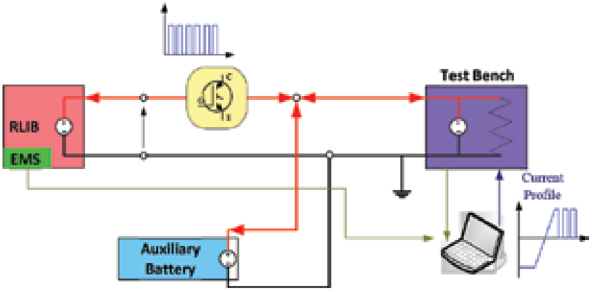


Figure 7. RLIB in parallel connection with auxiliary physical battery (ultracapacitor) controlled by EMS.

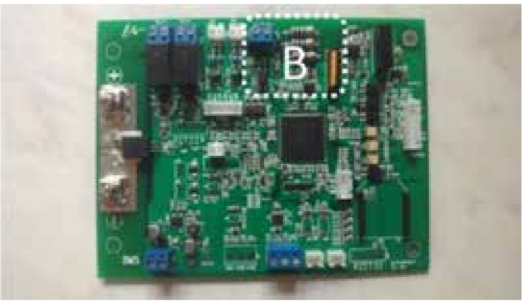


Figure 8. Architecture of EMS (symbol B is a safety device for estimating RLIB pack's insulation resistance).

6. Real-time simulator for optimizing the sharing ratio between RLIB and UC

Real-time simulators have been widely used in developing and verifying control strategies for power systems. Such devices are a powerful platform before on-board tests. Total analytical modules including EMS module is employed in the simulator. Detailed topology can be found in [41, 42]. In the system level, the control strategy from the vehicle side for the powertrain relating to the area electric range is validated [15]. Through the vehicle side, commands of torque and speed are sent out to the demand side of the motor simultaneously. Likewise, commands for gear shifting commands, the auxiliary system, and protection signals are passed from the vehicle side to other control units. It is originally developed in the environment of OPAL-RT®. An imaginary vehicle module is linked with the simulator via an analog/digital I/O interface, CAN bus, and RS-232. The off-line environment connected to real-time simulator provides sufficient capability for the development of EMS to select the optimized current sharing ratio between LIB and UC. The environment and interface model the dynamic response of load, multi-battery pack, and EMS.

7. Monitoring state of health (SOH)

State of charge and SOH define the most important amounts of charge and rated capacity loss of a battery, respectively. To determine these two parameters instantaneously, VOC

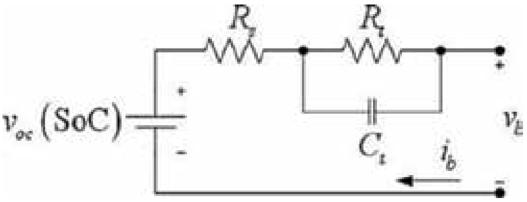


Figure 9. A generalized ECM for lithium batteries.

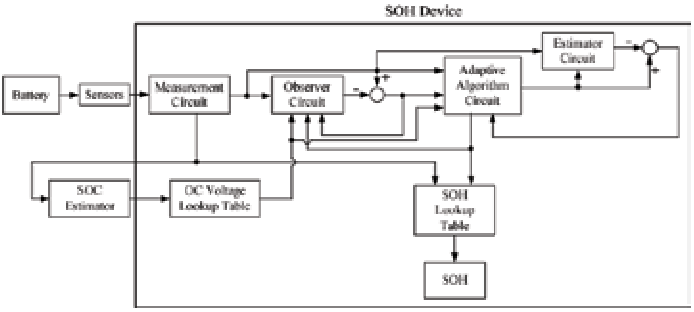


Figure 10. A flowchart describes how SoH functions.

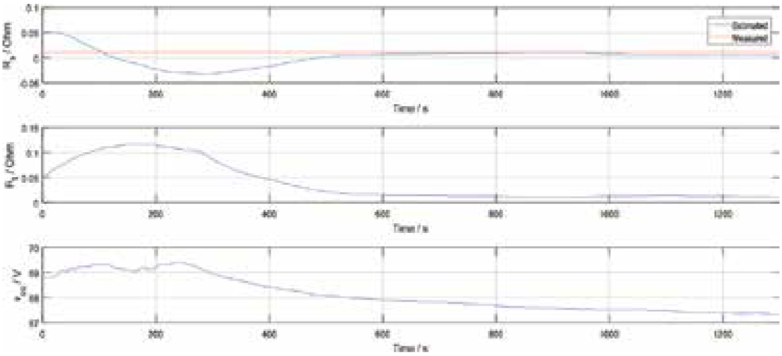


Figure 11. Comparison of estimated and measured internal resistances (1st, R_s; 2nd, R_t) and VoC (voltage of open circuit) in test case.

and internal resistance (IR) of the battery are indispensable. To guarantee the safety of RLIB, besides the insulation monitoring function shown in **Figure 8**, a simple, training-free, and easily implemented scheme in EMS is applied. This scheme is capable of estimating VOC and IR, particularly here for RLIB pack [53]. On the basis of an equivalent circuit model (ECM) shown in **Figure 9**, the electrical performance of the battery can be formulated into state-space representation. An underdetermined model's parameters can be arranged linearly so that an adaptive control approach can be applied. An algorithm of adaptive control is developed by exploiting the Lyapunov stability criteria as briefly illustrated in **Figure 10**. VOC and IR can be extracted precisely without limitations of input signals in the system, such as persistent excitation (PE). It enhances the application of this method for power systems. **Figure 11** shows one example for examining the algorithm by using adaptive control observer to estimate VOC and IR through the adaptive control approach. Estimation of SOH-sensitized IR can converge into a stable measured value in about 600(s).

8. Bench-test set-up and procedure

Two packs of RLIB are shown in **Figure 3**. Both of them are originally applied in pure EVs. After running on board for several years, they are used as experimental targets in this study, assembled with EMS, and installed in a test bench to simulate RLIB at WWTP.

Two types of LIB cells with a large difference in IR are employed in this study, and the specifications are listed in **Table 3**. An automated test bench with rated voltage and current of 500 V/450 A is utilized for the test. The initial rated voltage of RLIB is 70 V. A power pattern converted from the daily usage of electricity in WWTP is programmed into the machine for discharge/charge operation. In this study, all components are integrated in the laboratory, and the pattern of electricity is chosen for simulating the intermittent charging/discharging cycle of renewable energy and power accumulation due to the lack of in-situ energy consumption data. The duty cycle, current, and voltage of the RLIB terminal are monitored by the EMS. A total of 21 cells of LiFePO4 RLIB and three modules of LiMnNiCoO2 RLIB are modularized into two individual packs. A test case of RLIB connected with EMS is shown in **Figure 12**.

Figure 12. Implementation of RLIB with EMS and auxiliary physical battery (left: EMU; Central: $LiFePO_4$ LIB pack; and right: auxiliary physical battery).

Item	Unit	Energy density (Wh/kg)	IR(mΩ)	
			Pack	Total*
Molicel Module 10.96 V EME335-I403 (18650AG, 3S35P)	3 modules	100	3.27 × 3	
Pishuang Cell 38.4 Ah 3.2 V 400013201	21 cells	60	65.75	84.23

*Total IR is composed of internal resistance + harness resistance + fixture resistance.

Table 3. Specification of RLIB.

9. Verification of RLIB pack with EMS

To consider a real severe case, the current draw of the pattern of electricity is imposed on the RLIB pack [41, 42]. As shown in **Figure 13**, the accuracy of simulation with RLIB analytical module is examined by comparing with the measured results. The simulation with assumed linear VOC yields the deviation from the measured voltage curve. Otherwise, the simulation accurately predicts the response of RLIB.

Simulation results regarding voltage drop of a single RLIB pack in 100(s) under random load current is compared with the other case of RLIB pack connected with UC and active controlled by EMS (**Figures 14** and **15**). Effect of active controlled by EMS represented in DoD is not obvious. However, the energy consumption estimated from I^2*IR at both cases is shown in **Figures 16** and **17**, and EMS decreases 26% heat loss of RLIB.

In the bench test, the first case of $LiMnNiCoO_2$ RLIB pack in **Figure 18** shows the comparison of DoD with/without EMS under constant c-rate discharging. RLIB in active control of duty cycle 60% (solid line) shows the more stable and limit DoD than a single RLIB pack (dash line). Through real-time simulation by monitoring DoD, we optimize the best control duty of 60%. Here, IR of the RLIB pack plays an essential role in the distribution of DoD. To examine the control strategy even further, LiFePO4 RLIB is utilized as the DoD results (**Figure 19**). The effectiveness of EMS (solid line) is realized in comparison with the cases without EMS (point line) and single $LiFePO_4$ RLIB (dash line). To consider the stable DoD distribution of RLIB by using

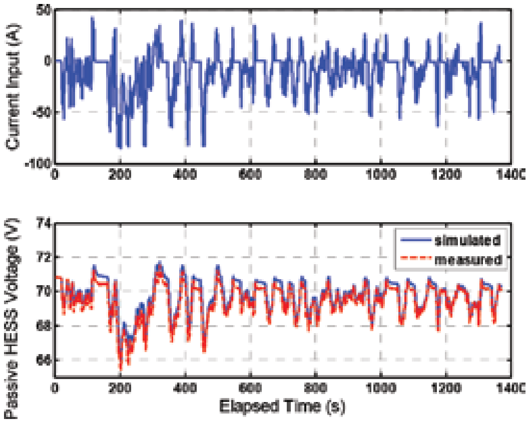


Figure 13. Comparison of simulation and measured results (upper: current; down: voltage) [41].

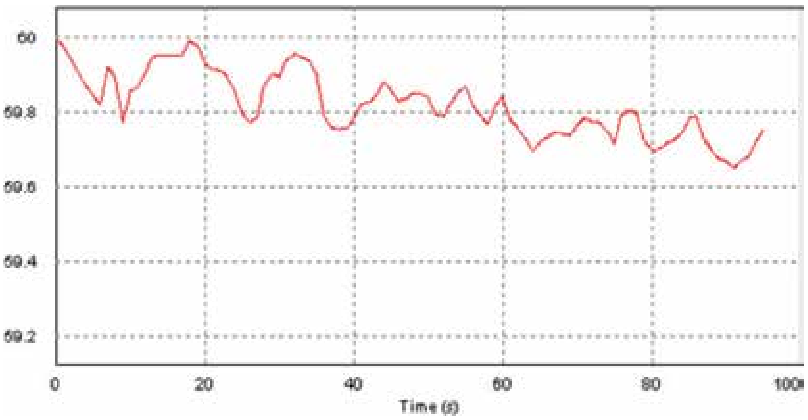


Figure 14. Voltage drop in simulation of 60 V single RLIB pack.

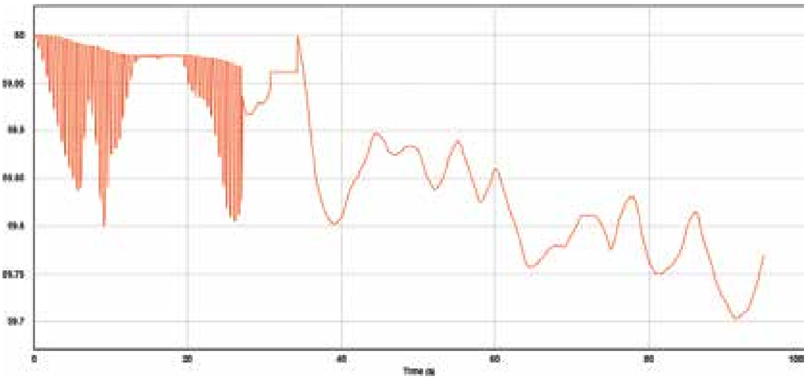


Figure 15. Voltage drop of 60 V RLIB pack which is in parallel connect with UC and active controlled by EMS.

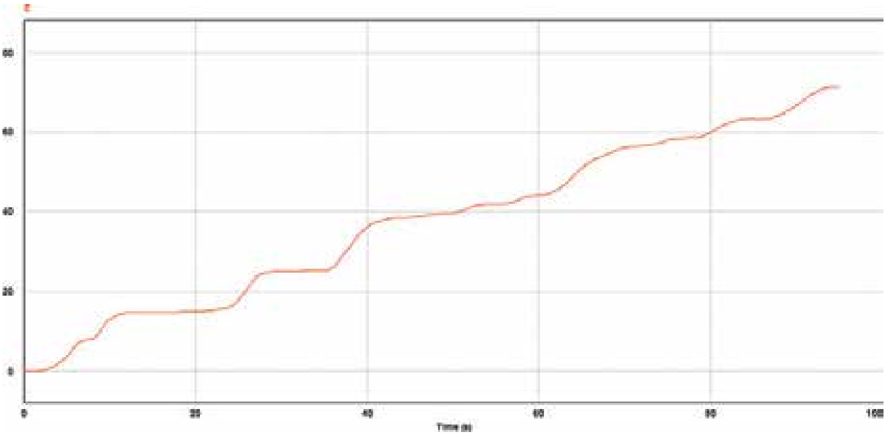


Figure 16. The energy consumption in the case of **Figure 14** (70 J) calculated by simulation.

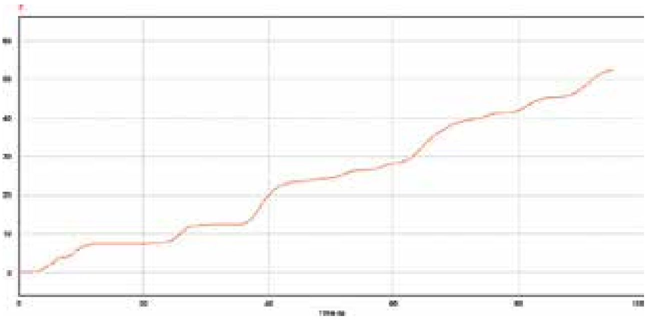


Figure 17. The energy consumption in the case of **Figure 15** (52 J).

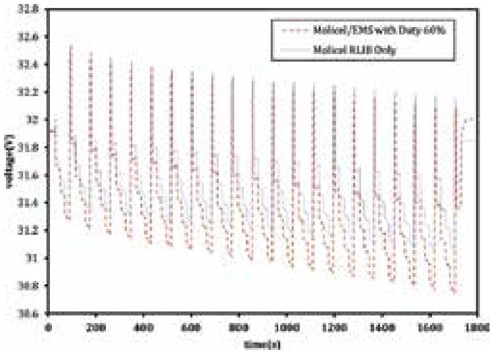


Figure 18. Comparison of DoD in single $LiMnNiCoO_2$ RLIB pack and RLIB with/without control.

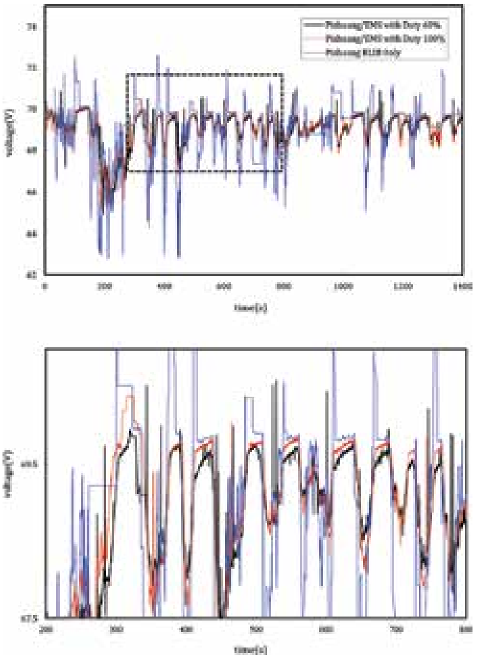


Figure 19. Comparison of DoD in single $LiFePO_4$ RLIB pack and RLIB with different PWM duty (upper: original; down: enlargement of dotted line in upper).

an auxiliary physical battery, individual IR of experimental batteries is listed in **Table 3**. IR of $LiFePO_4$ RLIB at 65.75 mΩ is much higher than that at 9.81 mΩ of $LiMnNiCoO_2$ RLIB pack and 3 mΩ of auxiliary physical battery (UC) by excluding harness resistance and fixture resistance. The load current provided by the auxiliary physical battery depends on each IR in parallel connection relative to RLIB (i.e., the lower the IR of the auxiliary physical battery, the higher current it can share) [42]. Consequently, a simple circuit converterless EMS in this study shows potential in controlling power flow to avoid the intense loading of RLIB. In particular, EMS with auxiliary high-power battery can increase the life cycle of RLIB [42]. Mass production of EMS has its potential in large-scale application of WWTPs. As **Figure 8** shows, average DoD in lifespan is nonlinear, which indicates that LIB can earn useful energy if average DoD is limited [44–48]. The distribution of DoD is directly related to life cycle as the formulation [48]. We apply this formulation to roughly estimate the benefit of using RLIB with EMS in this study.

10. Conclusion

In this study of applying RLIB in WWTP, a rough estimation by calculating the range of DoD by using EMS obtains the elongated range of an RLIB's life cycle up to 45% from 1100 to 1600 cycles at effective capacity of 80% based on the formulation in [48]. Under the consideration of environment, cost, and performance, the possibility of using automotive RLIBs is studied. One simple and converterless EMS is developed to use in a new RLIB pack. The bench test and rough estimation reveal that the EMS shows great potential in elongating life cycle and enhancing electricity charges. Furthermore, a simple, training-free, and easily implemented scheme based on ECM is applied in EMS. It is capable of online estimation of VOC and life cycle-sensitized IR for ensuring the safety of RLIB packs.

Next phase, a pilot run to install small-scale RLIB in Dihua plant is launched. For reflecting the best in-situ energy efficiency, remote power monitoring system is used to measure the peak and averaged energy consumption of aeration tank. It will function in the decision of optimized PWM signals for elongating the life cycle of RLIB.

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Section 4

Waste Management and Energy Recovery

A Value Chain Analysis for Bioenergy Production from Biomass and Biodegradable Waste: A Case Study in Northern Norway

Hao Yu, Elisabeth Román and Wei Deng Solvang

Additional information is available at the end of the chapter

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Abstract

During the past decades, the concerns of the depletion of fossil fuels and global warming caused by excess GHG emissions have become the most important driving force for the development and utilization of renewable energy resources. The successful experiences from the EU-28 have proved that bioenergy production from biomass and biodegradable waste is the most reliable and promising solution in today's renewable energy market. This chapter presents a general model for value chain analysis of bioenergy production from biomass and biodegradable waste. In addition, a feasibility study for establishing a bioenergy plant in the northern part of Norway is given to discuss the opportunities and challenges of bioenergy production. The feedstock of the planned bioenergy plant is from local agriculture, waste management sector, fishery and livestock industry. Value chain analysis is used to balance the economic and environmental influences of the bioenergy production in the area. Furthermore, suggestions for resolving the challenges and minimizing the potential risks of bioenergy production are also discussed in this chapter.

Keywords: value chain analysis, biodegradable waste, biomass, bioenergy, energy production

1. Introduction

Bioenergy production from biomass and biodegradable waste has received increasing focus due to recent acceleration in depletion of fossil fuels. The portion of renewable energies counted only 11% of total energy consumption while 74% is fossil energy in EU-28 in 2012 (**Figure 1(a)**) [1]. The heavy dependency on fossil fuels has resulted in two critical issues. First, fossil fuel is non-renewable and cannot be replenished by nature within a reasonable

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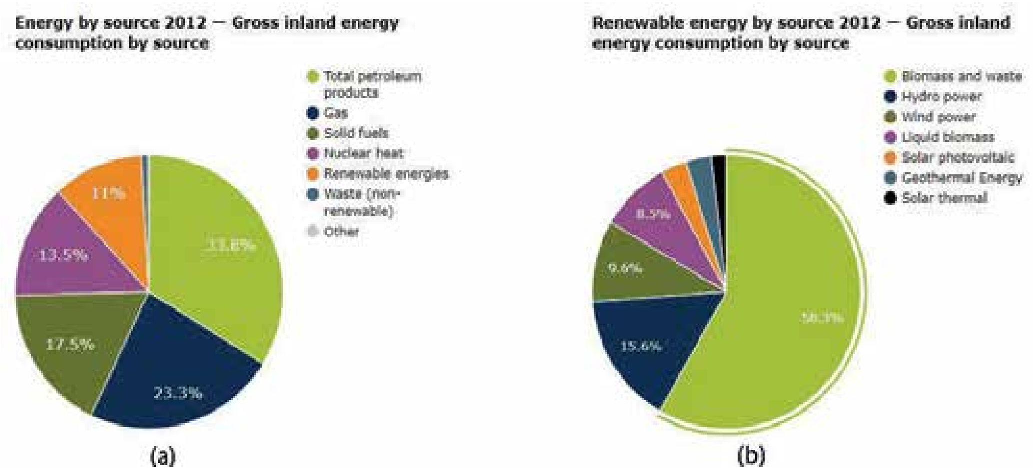

Figure 1. (a) Gross inland energy consumption by source of the EU-28 in 2012 and (b) renewable energy consumption by source of the EU-28 in 2012 [1].

timeframe. Moreover, the over-exploration and exponentially increasing consumption in recent years accelerate the depletion of fossil fuels. The estimated lifespan for the reserves of crude oil, natural gas and coal is approximately 35, 37 and 107 years, respectively [2]. The development of renewable energy resources becomes therefore of significant importance to meet energy demand in the near future. Second, the greenhouse gas (GHG) emission related to energy production and consumption from fossil fuels has played an important role to the global warming and climate change [3]. Both of them are believed to be the most significant challenges in the twenty-first century, which may lead to severe consequences for human's existence [4]. Due to these reasons, extensive efforts have been devoted in reducing GHG emissions in the past few decades. One of the most promising solutions to the abovementioned challenges is the explosion of renewable resources, i.e. wind, solar, tidal, biomass, etc., which not only provide an attractive alternative for energy production but also contribute to the mitigation of GHG emissions.

Bioenergy production from biomass and biodegradable waste is the most reliable renewable energy resource, which occupies predominant share of today's marketplace [5]. As shown in **Figure 1(b)**, the consumption of energy generated by biomass and biodegradable waste, liquid biomass, hydropower and wind power are 58.3, 8.5, 15.6 and 9.6%, respectively, and the other renewable resources including solar thermal, solar photovoltaic and geothermal constitute only 8% of the total consumption [1]. The reason for this high portion of bioenergy production in Europe is mainly due to the long-term efforts on developing legislative mechanism and technological means for recovering energy from biomass and biodegradable waste. For example, EU Landfill Directive (Council Directive 1999/31/EC [6]) implemented in 1999 sets the periodic target for the member states, and since then the amount of the biodegradable waste ended up in landfill has been dramatically reduced. EU Renewable Directive (Directive 2001/77/EC [7]) was implemented in 2001 and repealed in 2009 (Directive 2009/28/EC [8]) for promoting more applications of renewable energy resources. This has been followed up by Norwegian authority with a White Paper on Norwegian climate policies [9]. The White Paper documented particularly the large emissions of GHG from agriculture industry and waste management in Norway, and a specific goal is also stated to develop more bioenergy production plants in Norway. A joint treatment of biodegradable waste from both households and agriculture sections is emphasized.

As shown in **Figure 2**, only 35% of biomass and biodegradable waste are utilized in bioenergy production, and this will lead to a significant increase at 2.3 TWh (governmental target). Currently, the bioenergy production from biomass and biodegradable waste in Norway is also relatively small (0.5 TWh [10]). This can partly be explained by existing large energy production from other renewable resources, i.e. hydropower [11], which leads to fairly low energy price in general. Also, the limited infrastructure for bioenergy production and high investment are the main obstacles to an increased bioenergy production in Norway. The political willingness is to change the current situation of bioenergy production and establish more bioenergy plants in Norway. However, the governmental subsides and economic incentives for promoting bioenergy production have not been well established yet. In addition, some other institutional and regulative mechanisms should also be considered, i.e. competence enhancement, tax relief for transport utilizing biofuel, lowering gate fee for the delivery of biomass and biodegradable waste for energy production, etc.

In order to provide a better understanding of the bioenergy production from biomass and biodegradable waste, a general model for value chain analysis is first formulated and discussed in this chapter, and a feasibility analysis is then given to discuss the opportunities and challenges of establishing a bioenergy production plant in Northern Norway. The reminder of this chapter is structured as follows. Section 2 gives the definition and treatment methods of the feedstock of bioenergy production: biomass and biodegradable waste. Section 3 formulates a general value chain model of bioenergy production and performs the value chain analysis of bioenergy production. Section 4 presents a feasibility study for establishing bioenergy production plant in northern part of Norway. Section 5 summarizes the chapter and suggests for future studies.

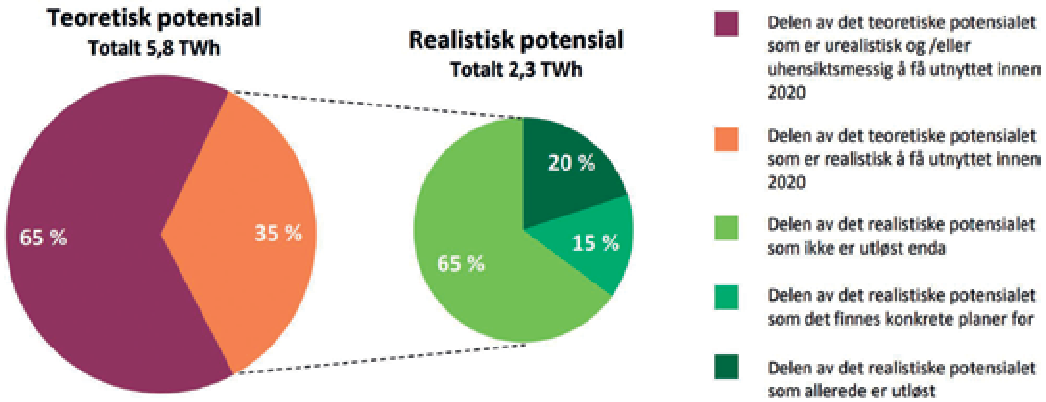

Figure 2. Potential bioenergy production in Norway within 2020 [10].

2. Bioenergy production from biomass and biodegradable waste

2.1. Biomass and biodegradable waste

Biomass is defined in twofold [12]. One is "*the total quantity or weight in a given area or volume*", which emphasizes its essential attribute as organic degradable substances. This definition is on a biological ecological basis. Another is "*organic matter used as a fuel, especially in a power station for the generation of electricity*", and this definition focuses the use of biomass for energy production. Similarly, Cambridge dictionary [13] defines biomass from both biological and engineering perspectives. From biological perspective, the biomass is defined as "*The total mass of living things in a particular area*". Herein, the inherent property of biomass as "living things" is focused. From engineering perspective, the biomass is defined as "*dead plant and animal materials suitable for using as a fuel*", and the property of biomass as a type of fuel is emphasized.

Biodegradable waste is another commonly used term to describe the feedstock of bioenergy production. Biodegradability is referred as the ability to decay naturally and non-harmfully [14]. According to Basel Convention [15], wastes are defined as "*substances or objects, which are disposed of or are intended to be disposed of or are required to be disposed of by provisions of national law*". Viewing from consumers' perspective, EU Directive 2008/98/EC [16] defines waste as "*an object the holder discards, intends to discard or is required to discard*". Based on the definition above, biodegradable waste is the portion of waste that can be decayed by nature.Biomass and biodegradable waste are the most important sources for bioenergy production, which mainly come from five sectors: forestry and timber, agriculture, fishery, waste management and wastewater treatment (**Figure 3**). It is noteworthy that the portion of biomass and biodegradable waste contributed by different sectors may vary dramatically from country to country, and the generation is significantly influenced by seasonality. Therefore, it is necessary to take into account of those variations and uncertainties in forecasting the amount of the feedstock for bioenergy production.

The difference between the two concepts is, compared with biodegradable waste, biomass that specifies a broader domain in which not only organic matters discarded by consumers

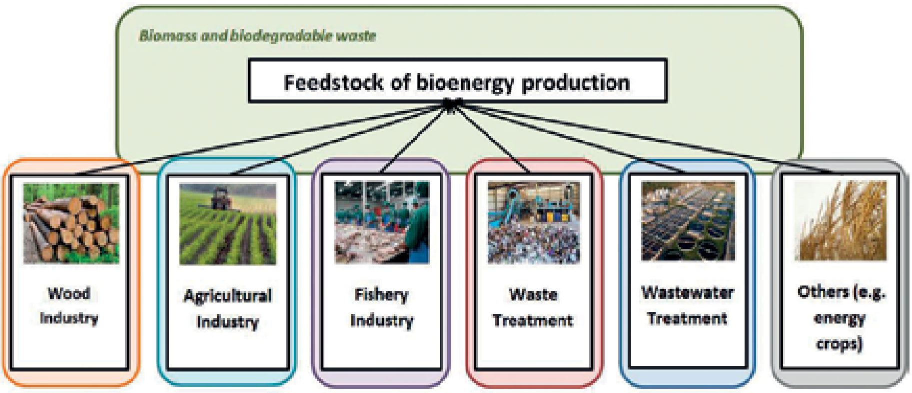

Figure 3. Sources of biomass and biodegradable waste.

but also the ones obtained intentionally for bioenergy production is included (e.g. energy crops). However, those two terms can sometimes be interchangeable when the feedstock of bioenergy production mainly refers to the organic substances that have lost their usefulness value to the consumers, and this applies to the case study presented latter in this chapter.

2.2. Treatment of biomass and biodegradable waste

Based on processing technologies, the treatment of biomass and biodegradable waste can be categorized into four types: direct combustion, thermochemical conversion, biochemical conversion and non-value-added treatment. The first three types are waste-to-energy (WTE) processes aiming to exploit the remaining value of biomass and biodegradable waste, and the last one usually refers to landfill at which the remaining value is eventually lost. Landfill is usually the least expensive but a non-sustainable way for biodegradable waste treatment [17], and the portion of biodegradable waste landfilled has continuously decreasing in Europe due to the rigorous and comprehensive legislations. WTE is the transformation of biomass and biodegradable waste into energy, and it initially specifies the production of power and heat through the combustion of biomass and biodegradable waste [18]. Nevertheless, its meaning has broadened to include other means of bioenergy recovery with the rapid technological development. Bioenergy has been extensively used in different industries, i.e. transport sector, power generation, heating, agriculture and chemistry industry [19]. **Table 1** illustrates the alternative means for bioenergy production and non-value-added treatment of biomass and biodegradable waste.

2.2.1. Direct combustion

Direct combustion has been widely used for over three decades in generating electricity and heat from biomass [20]. The principle is to utilize the heat generated by combustion of biomass for cooking, industrial process, direct home heating [21] or driving the steam power cycle for

Technology	Method	WTE/disposal	Product	Market
Thermochemical conversion	Pyrolysis	WTE	Bio-oil	Transport
	Gasification	WTE	Syngas	Chemistry, transport
Direct combustion	Incineration	WTE	Electricity, heat	Power, heating
Biochemical conversion	Composting	WTE	Fertilizer	Agriculture
	Anaerobic digestion	WTE	Biogas, fertilizer	Transport, agriculture
	MBT	WTE	Biogas, fertilizer	Transport, agriculture
Non-value-added treatment	Landfill	Disposal	N/A	N/A

Table 1. Alternative technologies for bioenergy production and non-value-added treatment of biomass and biodegradable waste.

electricity generation [22]. Due to the high level of moisture content, combustion promoters are usually used in order to improve the conversion efficiency. Coal is the most frequently used promoter, and co-combustion of biomass/biodegradable waste with coal has dominated the bioenergy production market in some countries, i.e. Sweden, Japan, etc. However, environmental challenges, i.e. emission of CO_2, SO_x and NO_x, from the co-combustion process are the major bottleneck for this method for bioenergy recovery [23]. Furthermore, as the common challenge of incineration plant, the flying ash is another pollutant that needs lots of efforts and costs to deal with so that the environmental influence is minimized.

2.2.2. Thermochemical conversion

Thermochemical conversion utilizes constant and high temperature combined with catalysts to convert biomass inside the boiler to biofuel and bioenergy through changing their physical properties and chemical structure [24]. The main technologies of thermochemical conversion of biomass and biodegradable waste include pyrolysis, gasification, liquefaction and torrefaction [25], among which pyrolysis and gasification are considered the most promising ones [26]. Pyrolysis is a fundamental method to transform biomass into crude-like liquid bio-oil [27], and after the chemical decomposition, the liquid bio-oil can be converted to the combustion fuels mainly used for transport and chemical industry [28]. The principle of pyrolysis process is the combination of thermal and chemical decomposition with the help of catalysts at relatively lower temperature (450–600°C) and longer vapor residence time in absence of oxygen for converting the organic substances to liquid bio-oil with charcoal and gases as the by-products [24, 29]. Gasification is another important thermochemical technology that converts different kinds of biomass into syngas. The main composition of syngas is methane, hydrogen, carbon dioxide and carbon monoxide, which are extensively applied in space heating, power generation, transport and chemical industry [30]. Different from pyrolysis, gasification process requires relatively higher temperature (700–1300°C) with the absence or limited oxygen environment in order to optimize the production of syngas [23, 26]. Recently, with the technological development, the probability of biomass and biodegradable waste gasification at lower temperature has also been discussed (e.g. [31]).

2.2.3. Biochemical conversion

Biochemical conversion utilizes biological and chemical processes with the help of aerobic or anaerobic microorganism to transform biomass into biogas and bio-rest, and the main biochemical technologies are composting, anaerobic digestion and mechanical biological treatment (MBT). Composting is an aerobic digestion process and a popular method for the treatment of biomass and biodegradable waste (e.g. Finland). The basic principle is to use biochemical process with the help of aerobic microorganism under open air environment for converting biomass into environmentally friendly bio-rest, which can be used as fertilizer. Anaerobic digestion is the most popular biochemical technology for bioenergy production, and thousands of anaerobic digestion bioenergy production plants have been established all over the world [32]. Through the biochemical decomposition process with the help of anaerobic bacteria at constant temperature in the absence of oxygen, the biomass can be transformed into not only bio-rest but also energy-rich biogas [33]. Biogas is mainly comprised by methane (60%) and carbon dioxide (40%), and it is mainly used as vehicle fuels after cleaned and upgraded [34]. In some cases, aerobic digestion and anaerobic digestion are combined for the treatment of biodegradable waste, e.g. wastewater sludge [35]. MBT combines mechanical pre-treatment and anaerobic digestion. The pre-treatment of biomass through different physical and mechanical processes breaks the physical structure and improves the quality of the input organic substances for anaerobic digestion [36], and the efficiency of bioenergy production is improved as well. Comparing with aerobic composting, both anaerobic digestion and MBT processes have much higher requirement for creating thermostatic and anaerobic environment.

3. Value chain analysis of bioenergy production from biomass and biodegradable waste

3.1. A value chain model for bioenergy production

The concept of value chain was originally proposed by Porter from financial perspective to account the sequential value creation and appreciation through the whole network comprised by different companies and enterprises [37]. This concept is usually accompanied with another word with similar meaning: supply chain (i.e. in [38, 39]). The difference between those two concepts is sometimes negligible especially when the value creation and appreciation process over the material flow are predominately accounted. However, a recent study by Holweg and Helo [40] has explicitly distinguished the two concepts from the perspective of their focuses. Supply chain management focuses on the links and interactions among different companies from the operational level considering strategies, methodologies, design, planning and operation of an efficient and effective multi-stakeholder inner- and/or inter-company network. However, value chain mainly concerns the value-added activities from one company to another within the network and the opportunities and challenges for maximizing the overall value creation and appreciation through the whole network.

The value chain of bioenergy production from biomass and biodegradable waste has been extensively modelled in the literature. Balaman and Selim [41] proposed a biomass-to-energy value chain model and a decision support tool for maximizing the overall profit generated through bioenergy production. A simplified value chain model is developed by Parker et al. [42], and the primary target of the model is to improve the economic value of biofuel production from biomass. An et al. [43] formulated a computational model to optimize the overall profit of a lignocellulosic biofuel value-added chain. Kim et al. [44] developed a four-echelon value chain framework for biofuel production through fast pyrolysis conversion. The maximization of the overall value creation from bioenergy production is focused by Kim et al. [45] and Dal Mas et al. [46]. The maximization of the value creation is sometimes formulated in an opposite way that minimizes the system cost. Chen and Fan [47] formulated a bioethanol production value chain model that applies mixed integer programming for minimizing the overall system cost. Aksoy et al. [48] developed an optimization model for minimizing the transportation cost of bioenergy production from woody biomass and mill waste. The environmental benefits of bioenergy production have been increasingly focused in recent years. A value-added chain of bioenergy production from biomass is modelled by Lam et al. [49], which focuses on the mitigation of carbon footprint of bioenergy production.

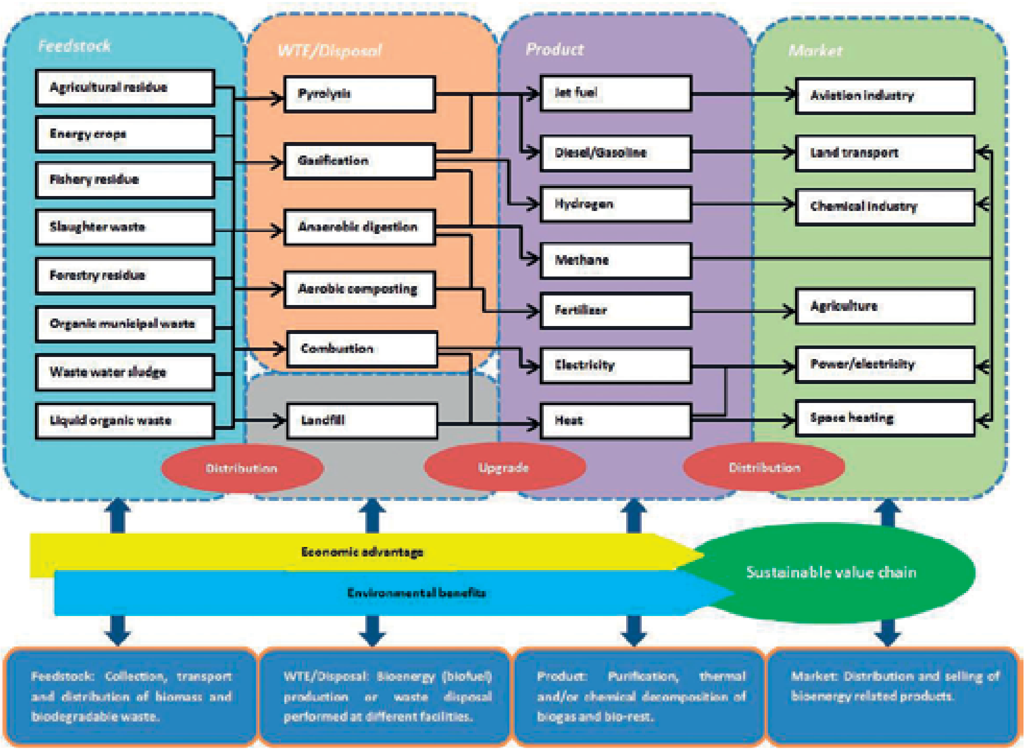

Figure 4. A general value chain model of bioenergy-from-biomass and biodegradable waste.

Bioenergy production from biomass yields economic benefits while reduces waste. However, it is not focused in the literature to account both economic and environmental benefits in the value chain of bioenergy production. In order to fill the literature gap, a general value chain model of bioenergy production from biomass and biodegradable waste is given in **Figure 4**. A typical value-added process of bioenergy production consists of the following activities:

- *Harvesting and collection of biomass and biodegradable waste from different sectors:* The main feedstock of bioenergy production includes agricultural residues, forestry residues, unban woody residues, fishery residues, slaughter wastes, animal manure, biodegradable municipal wastes and wastewater sludge, which are usually collected by different companies and/or public service departments.
- *Intermediate storage and distribution of biomass and biodegradable waste:* Road transport is the most flexible and commonly used way for the distribution of biomass and biodegradable waste; however, other means, i.e., train and ship, are also applicable especially for large amount of biomass and biodegradable waste transported over very long distance due to their relatively low costs.
- *Bioenergy production or proper disposal of biomass and biodegradable waste:* It is the most important value creation process that transforms the "raw materials" into "semi-finished

product". The main technologies are gasification, pyrolysis, aerobic composting, anaerobic digestion, direct combustion and landfill.

- *Purification and upgrade of the generated bioenergy:* This step is a critical value-added process that converts the "semi-finished product" into "finished product". The biogas and bio-fuel produced from previous step cannot be directly sent to market due to their complex chemical composition and low efficiency, so thermal and chemical decomposition, purification and upgrade are necessary in this phase. Besides, the model aims at maximizing the value creation of bioenergy production, so the utilization of landfill gas is taken into account in this value chain model.
- *Distribution and sales of the bioenergy as well as other by-products in the market:* This is the final step of the value chain of bioenergy production, where the value creation from the bioenergy production is eventually realized. The biogas, bio-fuel and bio-rest can be used in many different sectors including transport, aviation industry, chemical industry, agriculture, power generation and space heating.

3.2. Value chain analysis of bioenergy production

Value chain analysis has been widely used for investigating, through qualitative and/or quantitative methods, the value-added process in many different fields, i.e. mining industry, fishery industry, aviation industry, dairy industry, catering, production and manufacturing, etc. Conventionally, value chain analysis only emphasizes the value creation and appreciation from financial point of view. However, the increased concern on environmental challenges has led to much more focuses on the "green value-added process" in which not only economic value creation but also environmental value contribution through the entire material flow is accounted (e.g. in [50]). Bioenergy production is a value-added process from both economic and environmental perspectives, so value chain analysis is a reasonable basis for regarding pro et contra for bioenergy production. The value chain of bioenergy production comprises all joints in the flow from materials to products, and it can be analysed in such a way that all important joints are balanced out of a combination of economic and sustainable aspects all the way from cradle to grave.

Value chain analysis of bioenergy production provides decision makers with fundamental basis to divert biomass and biodegradable waste from landfill to WTE process. Previously, the value of biomass and biodegradable waste does not get enough attention, and a large portion is treated through non-value-added method that leads to great potential environmental problems. The model streamlines the value creation and appreciation of bioenergy production from biomass and biodegradable waste, and both economic advantages and environmental benefits are discussed. Bioenergy production takes a different point from waste management perspective to consider biomass as the "raw material" of the value chain and realize the transformation from "waste" to "financial and environmental value". The utilization of biofuel and biogas can dramatically decrease the high dependency on fossil fuels and improve the energy security of a country; further, the nature of self-replenishment of biomass and biodegradable waste makes them become one of the most important renewable energy resources. Besides,

Decision level	Decisions
Strategic decision	• Selection of WTE and treatment technologies • Selection of network configuration: location, capacity, etc. • Selection of potential suppliers and markets
Tactical decision	• Selection of equipment at different facilities • Aggregate production planning • Policy making for supplier and customer management
Operational decision	• Execution of the policies made in previous step • Scheduling and route planning

Table 2. Some strategic, tactical and operational decisions in the planning of a value chain for bioenergy production.

the GHG and hazardous gas emission can be reduced by the utilization of biofuel and biogas as the substitutes of fossil fuels in land transport and aviation industry [51].

The realization of an effective and efficient value-added chain of bioenergy production from biomass and biodegradable waste requires sophisticated decision tools for planning and developing an optimal and robust logistical network, and several strategic, tactical and operational decisions that have to be made are summarized in **Table 2**. In order to provide reliable support for decision-making, great efforts should be spent in the development of theoretical and computational models and decision support systems. Besides, the inherent characteristic of the seasonal availability of biomass and biodegradable waste generation makes the prediction of the feedstock of bioenergy production becoming extremely complicated. Therefore, the aforementioned factors have become the most challenging obstacles for realizing the value-added process of bioenergy production, and inappropriate decisions will hinder the achievement of maximum value creation and appreciation.

4. A value chain and feasibility analysis for establishing bioenergy plants in Northern Norway

4.1. Bioenergy production and bioenergy plants in Norway

The most significant energy consumption in Norway is electricity, which constitutes 88.8% of the total energy consumption in 2012, and it is approximately 17 times higher than the second largest one: petroleum products [52]. The main reason for the high dependency on electrical power is the lower price than other types of energy resources due to the rich reserves of hydropower for electricity generation. Hydroelectric power once contributed more than 99% electricity production in Norway [53], and the situation has not been changed until the latest years when energy production from biomass and biodegradable waste takes a small share from hydroelectric power.

All the Scandinavian countries, such as Denmark, Sweden, Norway and Finland, support the use of renewable energy resources for power generation and space heating, among which Norway has expelled itself as one of the best countries in Europe for renewable energy generation and consumption (58%) due to the high contribution from hydroelectric power [54]. However, the contribution from bioenergy production is extremely insignificant. Furthermore, compared with other Scandinavian countries where bioenergy has already played an important role in power generation, the share of electricity production by biomass and biodegradable waste in Norway is much smaller as shown in **Figure 5**.

The government in Norway has made an ambitious strategic plan for dramatically increasing the bioenergy production by 2020 through policy measures and financial supports [55]. For example, waste regulation has been implemented in Norway since 2009 implementing a ban, which specifies alternative ways for the treatment of biodegradable waste other than landfill. Besides, the forestry and agricultural legislation promote sustainable economic and environmental development in forest management and agriculture industry [53], so bioenergy production from forest and agricultural residues is encouraged. Further, the use of biofuels in land transport to replace fossil fuels is also encouraged in Norway. The road tax charges carbon emission for the vehicles using petroleum and natural gas products, but the cars using biofuels or biogas as the main power are exempt from this charge. In addition, plans for increasing the use of bioenergy for space heating of public and commercial buildings are also under development in order to reduce the fossil fuel consumption for heating.

In Norway, bioenergy production has two characteristics. First, compared with electricity generation, the use of biofuels and biogas in transport sector seems more attractive, because it decreases both the high dependency on fossil fuels and GHG emissions. Besides, Norway

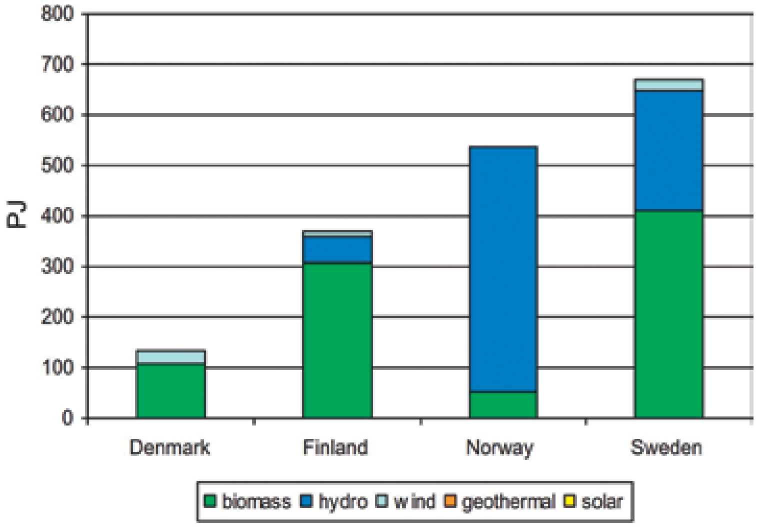

Figure 5. Power generation by sources in Scandinavian countries [54].

implemented the report of biofuels' usage in transport sector from 2014, and it has become one of the most important criteria to assess sustainability in transport sector. Therefore, thermochemical technologies, anaerobic digestion and MBT are widely used methods in Norway for biogas and biofuel production.

Figure 6 illustrates the established biogas and biofuel production plants as well as the demographic distribution, forestry and agricultural areas and road transport network in Norway. Currently, all the established bioenergy production plants are geographically located around the largest cities in the southern and central parts of Norway, and the northernmost bioenergy production plant is located at Verdal (North Trøndelag County). The established biogas and biofuel production plants in Norway have maintained well economic performance and contributed to the mitigation of GHG emissions. The critical success factors for bioenergy production in this region are summarized as follows:

- Dense population, agricultural and industrial clusters provide enough feedstock of biomass and biodegradable waste for bioenergy production.
- Well-developed road transport network provides easy access to the collection and distribution of biomass and biodegradable waste.
- Short distance between the bioenergy plants and collection points of biomass and biodegradable waste reduces the transportation and logistics cost.
- Governmental support for developing biogas and biofuel market, i.e. biogas used as the main fuel for the public transport in Fredrikstad, tax relief for biogas and biofuel in transport sector [53].
- Incentives for bioenergy production from biomass and biodegradable waste.

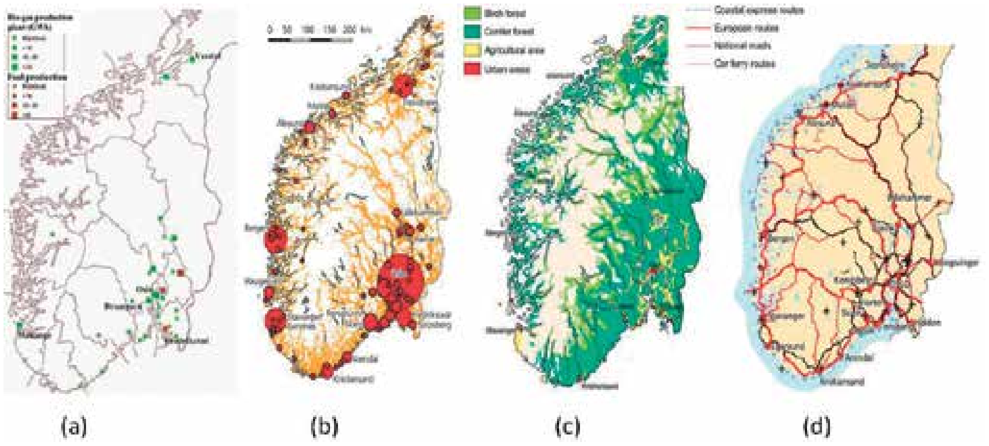

Figure 6. (a) Established biogas and biofuel production plants in Norway; (b) demographic distribution of southern and central parts of Norway; (c) forestry and agricultural industry in southern and central parts of Norway; and (d) road transport network of southern and central parts of Norway [11, 52].

The other characteristic of bioenergy production in Norway is the feedstock mainly comes from forestry/wood industry and waste management. **Figure 7** illustrates the sources of biomass and biodegradable waste for bioenergy production in Nordic countries. As shown in the figure, black liquor from chemical industry and wood residues from forestry industry are the most important resources for bioenergy production in Sweden and Finland, while the feedstock for bioenergy production in Norway and Denmark is mainly from waste management sector and forestry industry. Utilization of wood and forestry residues has been well-developed in Norway, and previous studies have discussed the policy structure [56], impact [57] and future potential [58] of bioenergy production from forestry biomass and waste. Besides, it is also noteworthy that energy crops, i.e. poplar, reed canary grass, willow, etc. [59], are not commercially cultivated in Norway, and the portion of bioenergy production from energy crops in the other Scandinavian countries is small as well. The main reason is that the long winter and cold climate in Scandinavian countries make it becoming economically unaffordable for cultivation of energy crops for bioenergy production in this area.

4.2. A feasibility study of bioenergy production in Nordland county

Bioenergy production in Northern Norway has been focused for many years. However, the negotiation between different stakeholders has been difficult reaching an implementation plan due to the conflicting interests involved. Earlier, the locations of landfill and composting plant were focused due to the consideration of the costs for waste collection and environmental risks of treatment facilities of biodegradable waste. Recently, the treatment plants have been equipped with closable ports, ventilation system, air cleaning system as well as other upgrades, which tremendously reduce the negative impact on the environment, and the focus on the energy recovery of biodegradable waste has been increasingly discussed.

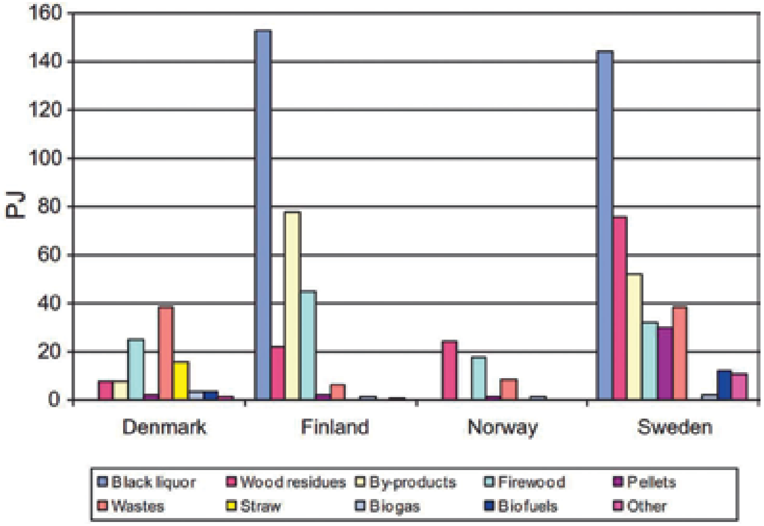

Figure 7. Bioenergy production by sources in Nordic countries [54].

In order to promote bioenergy production from biomass and biodegradable waste, Nordland County has drafted an initial plan for establishing a bioenergy plant at the costal-town Leknes. Leknes is the geographic centre of the famous Lofoten archipelago, and the close proximity to local agricultural areas, fishery and livestock industry is the main reason for the strategic decision of plant location. Besides, Leknes also has long-term experience in aerobic technologies, and the biomass and biodegradable waste generated at this region are treated at the composting plant. The upgrade of the aerobic composting plant to a MBT plant for producing biogas has been discussed for several years, and the strongest support is from local agriculture and livestock industry.

Leknes is one of the largest agricultural municipalities in Nordland County, and the meat production from poultry and livestock is on a large scale. The treatment of animal's manure is one of the most challenges in this area. Traditionally, the animal's manure is stored during winter time in barn and used as fertilizer for pasture grass production, but the emissions of methane and other hazardous gases from animal's manure are harmful to the environment. The planned MBT plant can effectively resolve this problem through converting the animal's manure into biogas and bio-rest, which can be used as vehicle fuel and fertilizer, so the plan is welcomed by local agriculture and livestock industry. Another supporter for bioenergy production from biodegradable waste is the local waste management company: LAS. Currently, LAS operates a landfill and a composting plant, and the anaerobic digestion facility planned in Leknes will be an attractive alternative for the treatment of biodegradable waste from LAS.

Figure 8 illustrates the value-added process of bioenergy production. The feedstock in this area is mainly from agriculture residues, livestock residues, fishery residues and municipal waste; however, biomass from forestry industry is not included in the current plan. The technology applied for bioenergy production in Leknes is MBT, and the main products are biogas and bio-rest. The biogas can be used as the fuels at land transport sector, and the bio-rest can be used as fertilizer for agriculture industry. Both biogas and bio-rest can either be used locally or sold in domestic/international markets.

The bioenergy production plant in Leknes aims at providing a sustainable solution in dealing with biomass and biodegradable waste from the municipalities in Nordland County. The most important factor of bioenergy production is to maintain economy of scale, so knowledge

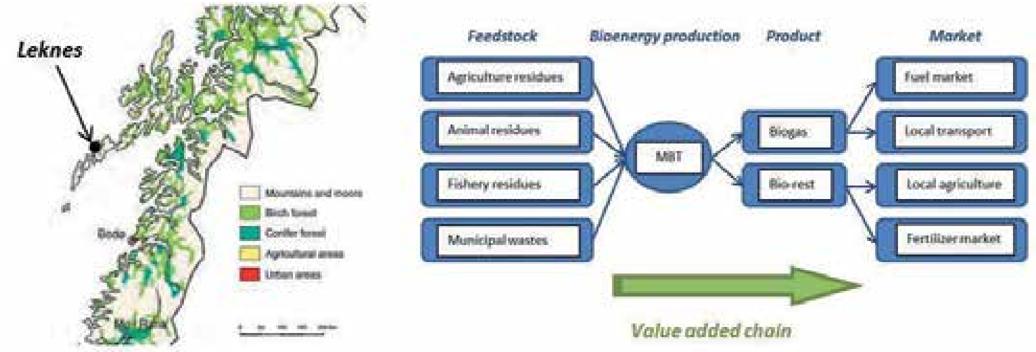

Figure 8. Value chain architecture of bioenergy production plant at Leknes [11, 52].

Biodegradable waste	**Estimated biogas output (m^3/year)[4]**	**Average factor[4]**	**Total biogas output (m^3/year)**	**Conversion factor (KWh/ton)[4]**	**Total estimated energy output (GWh)**
BMW[1]	204	180	2,340,000	1120	14.5
BWS[2]	93	102	142,800	444	0.62
AM[3]	19	19	95,000	190	0.95
Sum	N/A	N/A	2,577,800	N/A	16.3

[1] BMW: biodegradable municipal waste.

[2] BWS: biodegradable waste from slaughterhouse.

[3] AM: animal's manure.

[4] Basic data from Refs. [8, 63, 64].

Table 3. Estimated output amounts of biogas and bioenergy.

of annual generation of biomass and biodegradable waste is of importance. Estimation of the annual amount of three types of biodegradable waste is presented as follows:

1. Biodegradable municipal waste collected by regional waste management companies: 13,000 ton/year.
2. Biodegradable waste from slaughterhouse: 1400 tons/year.
3. Animal's manure from livestock industry: 5000 tons/year.

Calculation of the output of bioenergy production based on input amount provides valuable criteria for value chain analysis. Previous studies have formulated different models for the calculation of biogas output from different types of feedstock. Calculation in this chapter is based on the established models for biodegradable municipal waste and livestock residues from Norway [8], Sweden [60] and Denmark [61]. **Table 3** gives the estimated output of biogas from the three types of feedstock. The estimated output amount may be different from the actual amount, and this is due to the following reasons:

- The calculation of the outputs from the three types of biodegradable waste is conducted through the combination of different literatures. However, as a general rule, the biogas output in reality is usually lower than the estimated value.
- It is a common situation that different types of biomass are mixed in the digester for anaerobic digestion, and this will lead to different output amount with the separate digestion that estimated in the table. It is therefore impossible to foresee the exact output due to the biochemical decomposition of protein, carbohydrates, lipid differs and other substrates.
- Animal's manure has the least conversion efficiency, but its presence has great meaning for the conversion of mixed biomass and biodegradable waste due to the content of bacteria, nourishment and trace elements, which provide a stabilizing effect for the microbial digestion in the reactor tank. Researches on the optimization of biogas production have revealed that

compound mixtures of different substrates result in a microbial society with a larger diversity and are more stable [62], and that counts for an optimistic view of the calculated output.

Environmental challenges in high north arctic regions have been attracted much more focuses due to the potentially severe consequences such as melting glaciers and sea-level rise caused by global warming. GHG emissions have been proved to be the most important driving force for the global warming and climate change, and it has more influences on the vulnerable eco-environment. Thus, the environmental impact of bioenergy production is assessed by GHG emissions. Two types of GHG emissions are estimated in this chapter, one is the emissions of methane from stored animal's manure in livestock industry, and the other is the CO_2 emissions from the transportation to the MBT plant at Leknes.

The storage of animal's manure in winter not only occupies great space but also releases a large amount of methane. The treatment of animal's manure through bioenergy production can effectively resolve this problem. From the national perspective, Norwegian strategic document for bioenergy development estimates that the overall amount of animal's manure from livestock industry for potential bioenergy production in Norway is approximately 3.92 million tons, and this will lead to 305,000 tons CO_2-equivalent reduction of GHG emissions [10]. The amount of different animals in local livestock industry is given by the Farmer's Interest Organization at Lofoten region. Besides, we also presupposed an input amount of 5000 tons of animal's manure to a co-substrate-mixture at the bioenergy production plant. **Table 4** illustrates the annual emissions of methane from the animal's manure by sources. Based on the method provided in the governmental calculation, an overall 0.39 tons CO_2-equivalent reduction of methane emissions from local livestock industry can be estimated. Besides, the calculation also implies a reduction of fertilizer for pasture grass production; however, this can also be solved by utilizing the bio-rest from bioenergy production at Leknes. Development for utilizing wet bio-rest in agriculture has recently been proved to be a good fertilizer [64–66], and the close distance from local agriculture and livestock industry to the planned location of the MBT plant is another advantage for the utilization of bio-rest.

Animal	Amounts(1)	Individual methane emission factor (ton/animal/year)(2)	Total emission of methane (ton/year)
Cow (milk)	830	0.018	14.9
Cow (meat)	2100	0.0027	5.67
Hen	2600	0.0009	2.34
Pig	80	0.0071	0.568
Sheep	6800	0.0002	1.36
Goat	975	0.00012	0.117
Horse	69	0.00295	0.204
Sum			25.2

(1)Data provided from Farmer's Interest Organization, Lofoten region.

(2)Basic data from statistical yearbook of Norway [52].

Table 4. Emissions of methane from stored animal's manure.

GHG emissions associated with the transportation of biomass and biodegradable waste to Leknes are another important problem when the bioenergy production network is designed. In Nordland County, four regional waste management companies are involved in the collection, transportation and treatment of biodegradable waste in different municipalities: HRS, RENO VEST, IRIS and LAS. Currently, RENO VEST and LAS send their waste to Leknes for aerobic composting, and the organic waste collected at Narvik municipality is treated at the incineration plant at Kiruna in northern Sweden. Bodø municipality has its own composting plant for dealing with biodegradable waste. Obviously, both aerobic digestion and direct combustion are less sustainable than bioenergy production through MBT, so the planned MBT plant at Leknes becomes a suitable alternative for HRS and IRIS.

Table 5 presents the annual generation of biodegradable waste at different municipalities in Nordland County, and the distance from each municipality to Leknes is also given in this table. As shown in the table, transportation of small amount of biodegradable waste over long distance is necessary when the MBT plant is located at Leknes, and this will lose the advantage of economy of scale and increase GHG emissions. However, it is also the situation in today's waste management system. For example, the biodegradable waste collected at Narvik municipality travels 178 km to Kiruna for incineration. Compared with today's situation, only the transportation of biodegradable waste from Narvik and Bodø to Leknes will increase GHG emissions. **Table 6** illustrates the estimation of CO_2 emissions from the transportation of biodegradable waste to Leknes. The estimated CO_2 emissions are calculated based on the information provided by the waste management companies, which include the monthly generation of biodegradable waste in each community and the unit fuel consumption of waste collection and further distribution. Compared with the current waste management system, the CO_2 emissions of biomass and biodegradable waste transportation of the planned bioenergy production system will be increased by 19.3%.

Although it is difficult to formulate the complete value-added process of bioenergy production, we can still see a large potential of a sustainable solution for both energy production and waste management in Northern Norway. However, decisions must be made based on the consideration and justification of both benefits and challenges, and the interests of different stakeholders within the value chain of bioenergy production should also be taken into account. **Table 7** summarizes the opportunities and challenges of bioenergy production in Nordland County. As shown in the table, bioenergy production from biomass and biodegradable waste will deliver a great amount of biofuels and fertilizer to the market; besides, it will decrease GHG emissions as well as other environmental impacts from local agriculture, livestock industry and waste management. However, the costs and CO_2 emissions of the transportation in the overall bioenergy production network will be increased, and the operating costs of the MBT plant are higher in the cold regions due to more energy consumption for maintaining a constant temperature for anaerobic digestion. Further, there are uncertainties about the potential markets for biofuels and fertilizer, and the cost and CO_2 emission will be increased for the transportation of them to potential markets.

In order to resolve those challenges, policy support must be first formulated accordingly by the government so that the value added through the bioenergy production can be shared by all the stakeholders within the value chain. For example, governmental incentives or tax relief

Waste management company	Estimated waste (ton/year)	Distance to Leknes (km)(3)
Leknes (LAS)(1)	3400	0
Bodø (IRIS)(2)	5000	160(4)
Harstad (HRS)(2)	2300	263
Sortland (RENO VEST)(2)	2200	183
Narvik (HRS)(2)	2200	305

(1)Including the biodegradable waste from slaughterhouse.

(2)Data given by relevant waste management companies.

(3)Calculated on Google map.

(4)Including ferry boat transport.

Table 5. Generation of biodegradable waste in Nordland County.

Unit fuel consumption (L/km)	Annual transport distance (km/year)	Fuel consumption (L/year)	CO_2 emission (ton/year)(1)
LAS (local area) 0.58	24,000	13,920	37.4
RENO VEST 0.42	38,896	16,336	44
HRS, Harstad 0.48	62,660	30,077	39
HRS, Narvik 0.48	64,480	30,950	40
IRIS, Bodø 0.48	21,538	10,333	13
Total	211,564	101,616	173.4

(1)Calculated based upon Energilink [67].

Table 6. Estimated fuel consumption and CO_2 emissions from the transportation.

Opportunities	Challenges
• Large amount production of biofuels • Production of bio-rest/fertilizer • Increased use of biofuels in transport • Less GHG emissions from agriculture, livestock industry and waste treatment • Less environmental impact	• Increased costs for the transportation of biodegradable waste • Increased CO_2 emission from the transportation of biodegradable waste • Increased investment on bioenergy production in cold climate • Uncertain market demands • Cost and CO_2 emission related to the distribution of biofuels and bio-rest to potential market

Table 7. Opportunities and challenges of bioenergy production in Nordland County.

should be given to HRS and IRIS to compensate their increased transportation cost to deliver the biodegradable waste to Leknes, and this may also be achieved through implementing a lower entrance fee of the MBT plant. Besides, the successful example of using biofuels in the public transport sector in Southern Norway is also applicable for Nordland County, and the upgrade of buses for using biofuels should be subsidized by the local government. Further, the incentives or lower purchase price should also be given to the agriculture and pasture grass production in order to promote the local use of bio-fertilizer, which will tremendously decrease the cost and GHG emissions for delivering the bio-fertilizer to remote markets.

5. Conclusion

During the past decades, the concerns of the depletion of fossil fuels and global warming caused by excess GHG emissions have become the most important driving force for the development and utilization of renewable energy resources. The successful experiences from the EU-28 have proved that bioenergy production from biomass and biodegradable waste is the most reliable and promising solution in today's renewable energy market. This chapter studies bioenergy production from the perspective of value chain analysis. The method of value chain analysis has been developed for over three decades and extensively applied in analysing the value-added process of many different industries. In this chapter, a theoretical architecture for value chain analysis of bioenergy production from biomass and biodegradable waste is first formulated for streamlining the value-added activities in the bioenergy production network. In order to give a deep insight of the developed value chain model, we investigated the current situation of bioenergy production in Norway and compared that with other Nordic countries. The feasibility study for establishing a bioenergy production plant in Nordland County, which is located in the northern part of Norway, is also performed.

The value chain analysis of bioenergy production from biomass and biodegradable waste in Nordland County estimates both the potential amount of bioenergy output and the environmental impact, and suggestions for overcoming the challenges of bioenergy production are also given in this section. In order to better achieve the value-added process in bioenergy production in Nordland County, future studies are suggested from three aspects. First, information from other local industries should be investigated so that a complete value chain of bioenergy production can be formulated. Second, forestry residues are very important feedstock for bioenergy production in other places; however, it is not included in current plan for bioenergy production. Thus, further studies with inclusion of forestry waste as the feedstock of the MBT plant at Leknes should be carried out. Third, decision support tools for optimal design of integrated network for biodegradable waste transportation should be developed in order to balance both transportation costs and GHG emissions in an optimal manner.

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Conflict of interest

The authors declare no conflict of interest.

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Biochar Derived from Agricultural Waste Biomass Act as a Clean and Alternative Energy Source of Fossil Fuel Inputs

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Abstract

In this study, pyrolysis was used to upgrade the agricultural biomass waste (ABW) and increase its energy at pyrolysis temperatures ranging from 350 to 950°C and a residence time of 60 minutes. The produced biochars were characterized and their fuel qualities (such as, fixed carbon & carbon percentage, gross calorific value, pH and surface area) were evaluated. Physiochemical analysis showed that the biochar has improved fuel qualities compared to the raw biomass, such as decreased volatile matter, increased carbon content, pH and its gross calorific value with lower ash content. The evolution of derived biochar, as determined by TG-DTG and FT-IR, showed that most hemicellulose and cellulose were decomposed at below 350°C while the decomposition of lignin only occurs at higher pyrolysis temperatures. The biochars had increased ignition temperatures and higher combustion temperature regions compared to raw biomass feedstock. The present study showed that pyrolysis pointed the differences in fuel qualities among different agricultural biomass feedstocks. It also compromises with a promising conversion process for the production of biochar which has an alternative, clean and environment friendly energy source.

Keywords: biomass, pyrolysis, biochar, heating value, physiochemical properties

1. Introduction

The increasing demand of energy tied with the need to minimize the greenhouse gas emission and the menace of reducing oil reserves has brought into focus on the potential use of biomass as a renewable energy source [1, 2]. Most of the developed countries have already comprised this ideal concept of biomass use and application and their inexorable potential for development [3, 4].

Biomass energy is widely used in the third world principally in rural regions where it is frequently the main energy source for domestic purpose [5]. Most developing countries are still depending largely on availability of natural resources including coal, mineral mining etc. There are many alternative renewable energy sources which can be used in place of fossil and conventional fuels. Renewable energy resources are also often called alternative sources of energy. Renewable energy resources that use domestic resources have the potential to provide energy services with zero or almost zero emissions of both air pollutants and greenhouse gases [6].

Biomass can be converted into liquid, solid and gaseous fuels with the help of some physical, chemical and biological conversion processes [7, 8]. The conversion of biomass materials has a precise objective to transform a carbonaceous solid material [9]. The uses of agricultural by-products (like, coconut coir, rice husk, sugarcane bagasse, ground nut shell etc) are as fuel for cooking, cattle-feed and raw materials for paper and pulp industries. However, a large amount of this is wasted and creates disposal problem.

Pyrolysis is a new and green technology where these biomass wastes are converted into biochars [10]. Pyrolysis is a multi-product process which has shown the potential of recovering hydrocarbon liquid from carbonaceous solid waste, besides the char and the gas products. These carbonaceous solid wastes are renewable energy sources and therefore, the potential of converting them into useful energy [11].

Biochar is a value added product, which can be used for many purposes. It is highly carbonaceous and hence contains high energy content, comparable to high rank coals [12]. In addition, the heterogeneous reaction of solid carbon with oxygen is slower than homogeneous oxidation, which is relatively safe and easy to control. Biochar also has a large microscopic surface area due to the microspores developed during pyrolysis, and can be used for the filtration and adsorption of pollutants [12].

This study investigates the properties of biochar by slow pyrolysis [13] for coconut coir (CC) and ground nut shell (GNS) at different temperature at 350, 550, 750 and 950°C. Detailed properties of biochar from the samples were compared for the mass yield, elemental composition, pH, ash content and its functional group. Based on the results, the utilization of the biomass residues for biochar production was discussed.

2. Experimental

2.1. Selection of materials and biochar preparation

Coconut coir (CC) and ground nut shell (GNS) were selected as the representative agricultural waste biomass due to their high consumption potential in Jharkhand. The agricultural biomass was crushed to less than 5 mm and then dried at 105 ± 3°C for 24 h for pyrolysis study. These samples were air dried and undertaken for slow pyrolysis [14]. The pyrolysis was carried out at varying temperature (350, 550, 750 and 950°C) for 1 hour, after attaining these temperatures on heating @ 5–15°C/min.

3. Characterization

Proximate analysis was performed on agricultural waste biomass samples for the determination of ash, moisture, volatile matter and fixed carbon contents following the (ASTM E871-82, E1755-01, and E872-82) [9]. The fixed carbon (FC) content was calculated by difference.

ASTM D1762–84 standard method was followed for proximate analysis [15] for derived biochar in order to determine ash, moisture, volatile matter and fixed carbon contents presents in the biochar.

ASTM E777, 778 and 775 standard test method was followed for ultimate analysis [16] using (Vario EL III) CHNS analyzer.

The heating values of the samples were determined by bomb calorimeter (TESTMASTER T-451). A bomb calorimeter was used according to the (ASTM D4809-00) standard test method [17].

For pH determination, biochar slurry was prepared in (1.20, w/v) ratio of biochar and water [12]. PCS Testr™ 35 pH meter was used for pH determination.

ASTM E1131-03 standard method was followed for TGA/DTG by using a computerized NETZSCH SAT 449F3 thermogravimetry analyzer.

FT-IR spectroscopy was analyzed by a Perkin Elmer Spectra 2, USA, in which the pellet was prepared by mixing 1 mg of dried biochar with 200 mg of pre-dried and pulverized spectroscopic-grade KBr (potassium bromide).

4. Results and discussions

4.1. Proximate and ultimate analysis of CC and GNS samples

The proximate and ultimate analysis of the CC and GNS are shown in **Table 1**. From table, it is observed that the both the agricultural biomass have relatively less ash (0.94 and 1.79%, respectively); higher content of VM (80.73 and 79.54%, respectively) with FC (14.97 and 14.13%, respectively), and GCV (14.74 and 14.03 MJ/kg).

The contents of carbon, oxygen and hydrogen in all the feedstocks are (C, 47.78 and 45.50%; O, 46.14 and 48.45%; H, 5.87 and 5.44%, respectively). Further the lower content of hetero elements (N, 0.19 and 0.46% and S, 0.11 and 0.15%, respectively) in CC and GNS are advantageous for environmental disquiets. Also agricultural biomass at thermo-chemical treatment releases less toxic gases (such as, SOx and NOx gases) comparable with fossil fuels. Than which we can say biomass are environment friendly and clean energy source.

ABW samples	**Proximate analysis**				**Ultimate analysis**					**GCV(MJ/kg)**
	M %	**VM** %	**Ash** %	**FC** %	**C** %	**N** %	**H** %	**S** %	**O** %	
Coconut coir (CC	3.36	80.73	0.94	14.97	47.78	0.19	5.87	0.11	46.14	14.74
Ground nut shell (GNS)	4.54	79.54	1.79	14.13	45.50	0.46	5.44	0.15	48.45	14.03

Table 1. Proximate and Ultimate analysis (as received basis) of CC and GNS.

Biochar samples	**Temperature (°C)**	**Biochar energy yield (%)**	**pH**	**GCV (MJ/Kg)**
CCC_h	350	30.60	8.04	16.40
	550	28.34	9.49	19.73
	750	25.65	10.11	22.26
	950	22.04	11.08	23.12
$GNSC_h$	350	48.50	7.70	17.58
	550	41.39	8.83	20.51
	750	38.53	9.50	22.46
	950	35.35	10.41	23.50

Table 2. Physiochemical characteristics of CCC_h and $GNSC_h$ at different temperatures.

4.2. Yield, pH, and GCV of the biochars

Physiochemical characteristics like, Yield%, pH, and GCV of the derived biochars at different temperatures from CC and GNS are shown in **Table 2**. From this table it is observed that there is relatively higher percentage of yield at 350°C of pyrolysis, which further decreases with increase in temperature up to 950°C. From this table, it is observed that there is relatively higher yield of chars at lower temperature of pyrolysis, which further decreases progressively with increase in temperature. Reduction in the bio-char yield at high temperatures is attributable to undergoing the secondary reactions of the bio-char formed during the primary pyrolysis, which lead to the formation of liquid and gaseous products at the cost of solid char [18]. The energy given to the biomass at high temperature may exceed the bond breaking energy which supports the release of the volatile components of the biomass in the form of gases resulting in less char yield [19]. The reduction in the bio-char yield with increase in pyrolysis temperature is also reported by other workers [20, 21]. As with the biomass feedstocks, the char products have energy values roughly related to their carbon contents. Release of this energy by combustion can again be considered as renewable and is largely carbon neutral; the carbon returned to the atmosphere as carbon dioxide is the same as would otherwise have resulted from biomass decomposition. If the char product is not burnt, but retained in a way that the carbon in it is stable, then that carbon can be equated to carbon dioxide removed from the atmosphere and sequestered.

The pH values of coconut coir char (CCC_h) and ground nut shell char ($GNSC_h$) varies from (8.04–11.08) and (7.70–10.41) respectively are also increase with increase in pyrolysis temperature. Biochars with higher pH and significant surface area are suggestive for their better application potential in reducing the soil acidity and treating the soil and water contaminated with toxic elements and organic pollutants [22–24]. Similarly the heating value (GCV) for these biochars also varies in the range 16.40–23.12 MJ/kg and 17.58–23.50 MJ/kg respectively [25]. The increase in the GCV of the biochars is attributable to the heat endorsing components (like FC, C, and H) present in these agricultural wastes biomass.

4.3. Proximate and ultimate analyses of CCC_h and $GNSC_h$ at different pyrolysis temperature

Proximate and Ultimate analysis of CCC_h and $GNSC_h$ are shown in **Table 3**. volatile matter (VM) content of biochar decreases with increase in pyrolysis temperature i.e., 32.48–5.56% and 30.80–6.48% in case of CCC_h and $GNSC_h$ respectively. The presence of lignin in the agricultural biomass waste material can partially resist pyrolytic decomposition at lower temperature but not in case at temperatures as high as 950°C [26]. The CCC_h and $GNSC_h$ showed a high ash content, and this may be because of the partial change in the composition promoted by a possible relation between organic and inorganic constituents [26]. It can be seen that biochars with higher content of ash generally have the lower values of fixed carbon and vice versa. Similarly fixed carbon (FC) in CCC_h and $GNSC_h$ varies from 45.25–84.32% and 49.91–85.06%, respectively.

Further the ultimate analysis of CCC_h and $GNSC_h$ varies significantly in respect of C, H, N, S, and O contents, which is tabulated in **Table 3**.

FT-IR Analysis of the CC, GNS, and their derived char at different pyrolysis temperature.

Figure 1 (a) and **(b)** shows the FTIR spectra of CC, GNS, and their derived char at different pyrolysis temperatures. These graphs are plotted against wave numbers and transmittance

Biochars	Pyrolysis temperature (°C)	VM%	Ash%	FC %	C %	N %	H %	S %	O %
CCC_h	350	32.48	22.27	45.25	49.73	1.14	4.50	0.18	44.45
	550	21.80	19.78	58.42	64.40	1.01	3.78	0.16	30.65
	750	6.38	15.62	78.05	80.69	0.79	2.55	0.16	15.81
	950	5.56	10.12	84.32	87.45	0.47	2.02	0.17	9.89
$GNSC_h$	350	30.80	19.29	49.91	56.20	0.86	5.61	0.09	37.24
	550	19.56	15.34	65.10	71.78	0.79	3.46	0.09	23.88
	750	8.67	10.21	81.12	83.49	0.58	2.39	0.07	13.47
	950	6.48	8.46	85.06	87.78	0.43	2.11	0.06	9.62

*Air dried basis.

Table 3. Proximate* and ultimate analysis of CCC_h and $GNSC_h$ at different pyrolysis temperature.

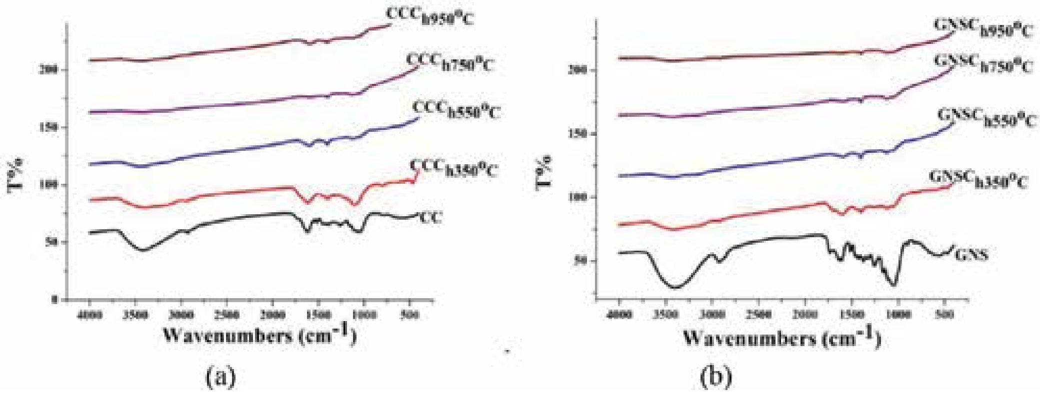

Figure 1. FTIR analysis of (a) coconut coir (CC) and (b) ground nut shell (GNS) and their derived char at different temperatures.

percentage, which show the aliphatic loss in their functional group. The AWB samples (CC and GNS) have bands at 3401-3420 cm^{-1} (O-H stretching), 2940-2955 cm^{-1} (CH, CH_2 stretching), 1600-1645 cm^{-1} (C=C stretching), 1510-1520 cm^{-1} (benzene ring), 1420-1470 cm^{-1} (aromatic skeletal vibrations; asymmetric in -CH_3 and -CH_2-), 1310-1380 cm^{-1}(Phenolic OH; aliphatic C-H deformation vibrations in cellulose and hemicelluloses), 1210-1245 cm^{-1}(C-O-C stretching in alkyl aromatic), (1140-1161 cm^{-1} (C-O-C asymmetry stretching), 1030-1060 cm^{-1} (C-O stretching).

From the FTIR spectra of CHC_h and SBC_h, it is seen from **Figure 1 (a)** and **(b)**, that the aliphatic losses are represented by the C-H stretching (2800-2950 cm^{-1}) with increasing in pyrolysis temperature [27]. The representative peaks seemed for aromatic carbon C-H stretching (3050-3000 cm^{-1}), C=C (1350-1450 cm^{-1}), C-C, and C-O stretching (1580-1730 cm^{-1}) [28–30]. This is obviously because the pyrolysis temperature amends the functional group. It can be seen from result aliphatic C group decreases but aromatic C group increases [31]. But, when the pyrolysis temperature becomes high, the intensity of the bands such as that of the hydroxyl groups (3210-3450 cm^{-1}) and aromatic groups (1550-1650 and 3050-3250 cm^{-1}) [27, 32], gradually diminishes.

5. Combustion behavior of biochar

Figures 2 and **3** shows the TG/DTG curves for the CC, GNS and their derived biochars, with the combustion parameters summarized in **Table 4**. From the curves, it can be seen that the combustion behavior of the agricultural biomass changed significantly after pyrolysis. For CC and GNS, a sharp DTG peak was observed centered at about 296°C and a weight loss of 75–85% was occurred at 350°C. The combustion of CC involves mainly volatile matter combustion, which was ignited at a low temperature of 283°C due to the high reactivity of volatile matter. The rapid weight loss in CC and GNS within a short time at the lower temperature

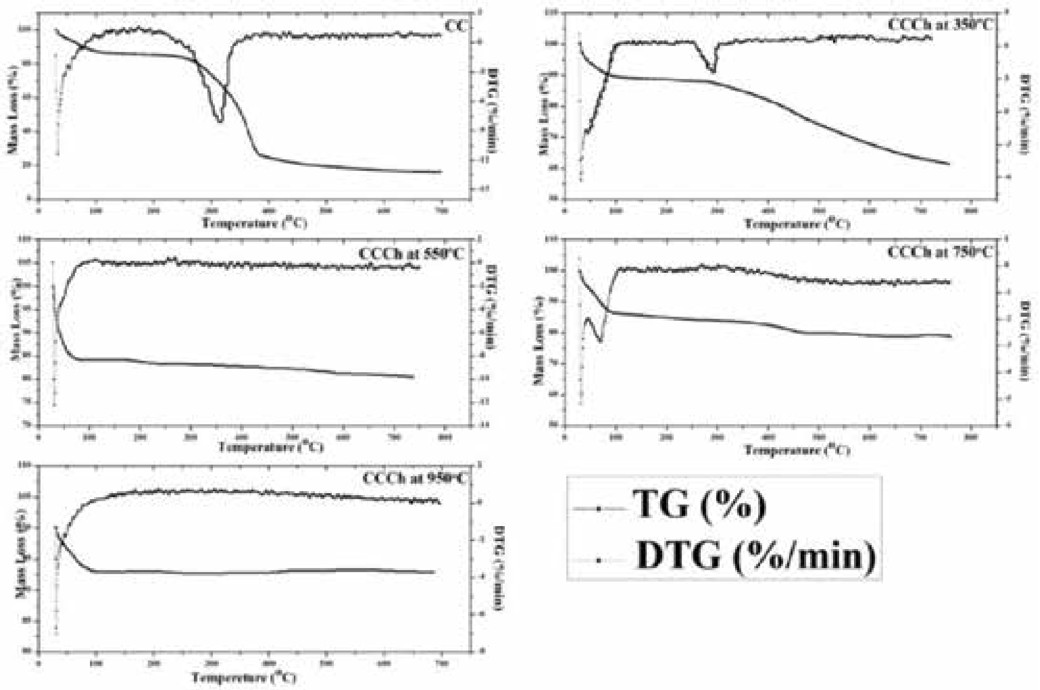

Figure 2. TG and DTG curve of coconut coir (CC) its derived char at different temperatures.

range implies that there was incomplete combustion with low efficiency and high pollutant emissions [33].

Compared to raw biomass, the reactivity of the biochar decreased, resulting in a higher ignition temperature and combustion in a wider temperature range. The elevated combustion temperature with high weight loss rate implies improved combustion safety, increased combustion efficiency and decreased pollutant emission. These combustion characteristics of biochar are significant improvements over raw biomass feedstock as a fuel [33, 34]. Generally, two separate peaks can be seen for all derived biochars in an inert atmosphere [35], where the first one is assigned to the thermal decomposition of hemicelluloses and the second one is for the cellulose and lignin decomposition, which covers a longer range. From the DTG profile, the initial mass loss at about 70°C is due to the moisture present in the sample. In the second stage from 295 to 308°C with maximum weight loss rate obtained at 310°C is attributable to the hemicelluloses degradation. The third stage appeared from 355 to 405°C with maximum decomposition rate at 355°C. Compared with these three components, lignin was the most difficult one to decompose even at higher temperature.

From the DTG curve of $\mathrm{CCC}_{\mathrm{h}(350^{\circ}\mathrm{C})}$ and $\mathrm{GNSC}_{\mathrm{h}(350^{\circ}\mathrm{C})}$, it can be seen that the degradation of cellulose and hemi-cellulose is complete. But the DTG profile of the $\mathrm{CCC}_{\mathrm{h}(550\text{–}750^{\circ}\mathrm{C})}$ and $\mathrm{GNSC}_{\mathrm{h}}$ $_{(550\text{–}750^{\circ}\mathrm{C})}$ indicates that the decomposition of lignin is complete, and attains steady state at $\mathrm{CCC}_{\mathrm{h}(950^{\circ}\mathrm{C})}$ and $\mathrm{GNSC}_{\mathrm{h}(950^{\circ}\mathrm{C})}$.

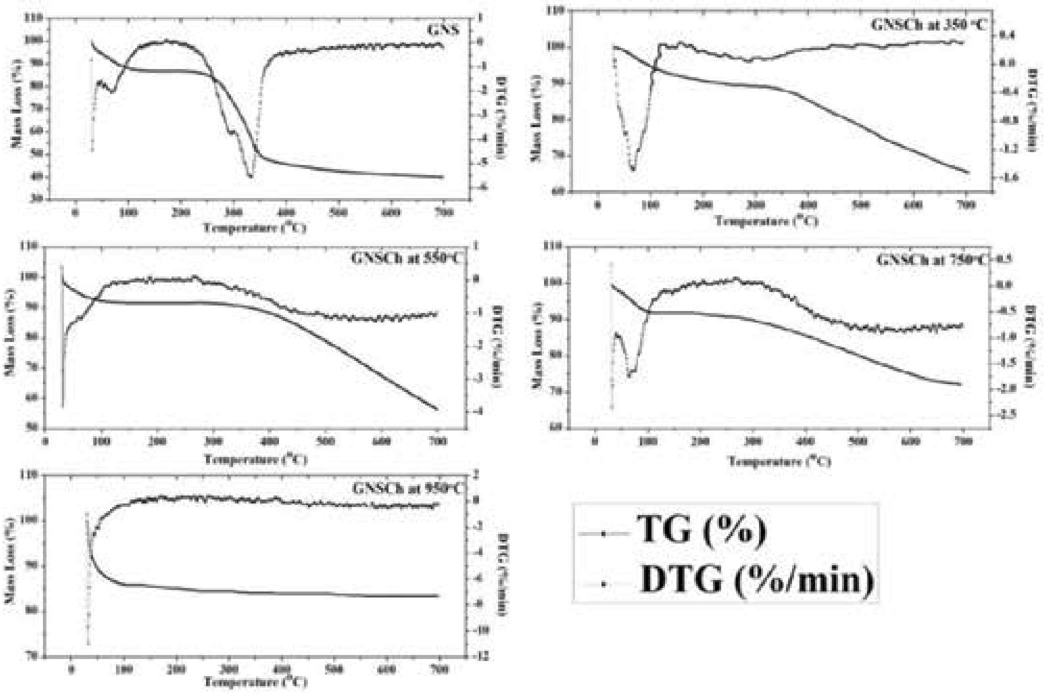

Figure 3. TG and DTG curve of ground nut shell (GNS) its derived char at different temperatures.

Sample	T_i	T_m	T_b	R_{max}	D_i ($\times 10^{-3}$)
CC	195	300	375	1.09	0.57
$CCC_{h(350^\circ C)}$	295	395	490	0.55	0.29
$CCC_{h(550^\circ C)}$	—	—	—	0.51	0.27
$CCC_{h(750^\circ C)}$	375	530	696	0.38	0.20
$CCC_{h(950^\circ C)}$	—	—	—	0.19	0.09
GNS	240	310	375	1.12	0.65
$GNSC_{h(350^\circ C)}$	298	355	400	0.7	0.37
$GNSC_{h(550^\circ C)}$	375	525	695	0.51	0.27
$GNSC_{h(750^\circ C)}$	400	505	698	0.4	0.21
$GNSC_{h(950^\circ C)}$	—	—	—	0.14	0.07

Table 4. Combustion parameters of agricultural waste biomass samples and their derived biochar.

For evaluation of the ignition performance, ignition index (Di) of the biomass and biochar was calculated with the following equation [36]:

$$D_i = R_{max}/(t_{max} \times t_i),$$

where R_{max} is the maximum weight loss rate,

t_{max} and t_i are corresponding to the time of the maximum weight loss rate and ignition temperature, respectively.

Higher values of ignition index (D_i) are indicative of better ignition performance [37]. As shown in **Table 4**, the coconut coir and ground nut shell derived biochars have lower D_i values than its corresponding raw samples, and the D_i values decreases with increase in temperature.

5.1. Environmental implications of biochar production processes

Pyrolysis produces high energy-density fuels, such as biochar. Biochars are non-polluting and reliable, and also contain oxygen levels of 10–45% [38]. Biochars have efficient as eco-friendly media for removal of organic and inorganic contaminant in aqueous environment such as polluted soil, water, waste effluents among others. Application of biochars to soils has been examined at the field scale as an in-situ remediation strategy for both organic and inorganic contaminants to determine their ability to increase the sorption capacity of varying soils and sediments [39]. Biochars may also help in mitigating some negative environmental effects by addressing the climate changes which in-turn may lead to economic as well as environmental benefits. Thus the inimitable characteristics of biochar in C-sequestration as well as their biodegradability make them dynamic role in this field. Thus the usage of biochars in various applications will prove absolutely beneficial in the near future.

Pyrolysis processes can be used as part of renewable energy systems based on biomass in a number of ways. Such systems can offset use of fossil fuels and so avoid associated emissions of greenhouse gases. The gas product through pyrolysis process is termed synthesis gas, shortened to syngas. It is generally composed of carbon dioxide (9–55% by volume), carbon monoxide (16–51%), methane (4–11%), hydrogen (2–43%) and hydrocarbons in varying proportions. The gases are usually present with nitrogen introduced to inert the pyrolysis process, this can be treated as a diluent and discounted for material balancing. The carbon dioxide and nitrogen provide no energy value in combustion; the other gases are flammable and provide energy value in proportion to their individual properties. The use of energy in the gas can be considered as renewable and largely carbon neutral. No special consideration of the carbon dioxide in the pyrolysis gas is required as it is not additional to what would result from biomass decomposition.

6. Conclusion

Biochars with upgraded fuel qualities were successfully produced from pyrolysis of agricultural biomass waste (ABW). This study demonstrates the type of feedstocks and pyrolysis temperature strongly stimulus the characteristics of the biochar. Increase in pyrolysis temperature, percentage of yield, VM and H, of all the bio-chars decrease; but FC, C, degree of carbonization, GCV, and pH increase. The combustion behaviors of biochars were distinct from raw agricultural biomass, with increased maximum weight loss, raised the ignition temperature and wide combustion ranges at higher pyrolysis temperatures. The conversion of agricultural biomass wastes by pyrolysis to biochar can be a potential option to utilize these wastes for various sustainable purposes like as a as a substitute of renewable energy sources and which we used as a clean and environment friendly energy source.

Symbols and nomenclature

VM%	Volatile Matter Content (weight %),
FC%	Fixed Carbon Content (weight %),
C%	Carbon Content (weight %),
N%	Nitrogen Content (weight %),
H%	Hydrogen Content (weight %),
S%	Sulfur Content (weight %),
O%	Oxygen Content (weight %),
GCV	Gross Calorific Value,
MJ/kg	Mega joule per kilogram,
CC	Corn Cob,
$CCC_{h(350^{\circ}C)}$	Corn Cob Char at 350°C,
$CCC_{h(550^{\circ}C)}$	Corn Cob Char at 550°C,
$CCC_{h(750^{\circ}C)}$	Corn Cob Char at 750°C,
$CCC_{h(950^{\circ}C)}$	Corn Cob Char at 950°C,
GNS	Ground Nut shell,
$GNSC_{h(350^{\circ}C)}$	Ground Nut Shell Char at 350°C,
$GNSC_{h(550^{\circ}C)}$	Ground Nut Shell Char at 550°C,
$GNSC_{h(750^{\circ}C)}$	Ground Nut Shell Char at 750°C,
$GNSC_{h(950^{\circ}C)}$	Ground Nut Shell Char at 950°C,
t_{max}	time of the maximum weight loss rate,
t_i	ignition temperature,
Di	ignition index,
R_{max}	maximum weight loss rate

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