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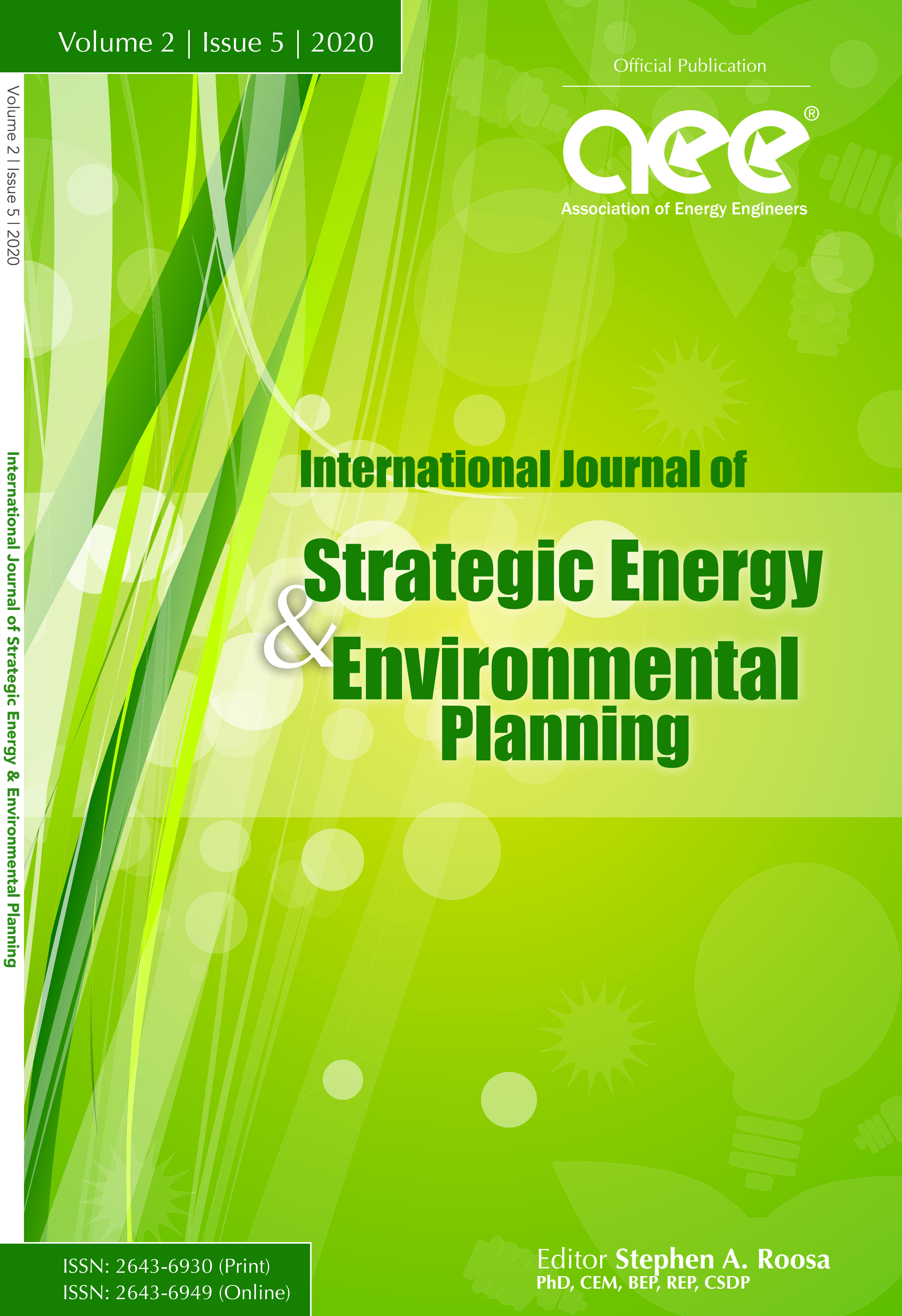

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Stephen A. Roosa, Ph.D., CEM, Editor-in-Chief

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Contents

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Reimagining Nuclear Energy

The vision for clean energy grids often involves local generation of electricity using a renewable energy source, perhaps from wind and solar power. Excess power could be stored for later use or directed to an electrolysis facility to create hydrogen and oxygen using water. The hydrogen would be piped to storage and used for electrical generation. Another alternative is to generate electricity with package nuclear power systems.

Uranium is a fossil fuel. It is often classified as a clean energy source when used for nuclear power processes that generate electricity. This is because greenhouse gases are not emitted when electricity is generated. When we think of nuclear plants we focus on utility-scale generation facilities. Small nuclear reactors have the potential to power the microgrids of the future. Advanced small modular reactors (SMRs) are being developed in the U.S. which can be used for process heat and electrical power generation. They vary in output from a few to hundreds of megawatts and use various types of liquid coolants. SMRs offer advantages that include their small size, variable output capabilities, reduced capital investment, ability to be sited in locations not possible for larger nuclear plants, and the ability to incrementally add power [1]. SMRs can store two years' or more of their fuel requirements on-site, allowing them to maintain power after extreme weather events or other threats to the electric grid [2]. SMRs can operate either independently or connected to the grid, allowing them to power a campus facility or small community in the event of grid failure [2].

The next generation of small reactors might use thorium as fuel and molten salt as a heat sink to provide electricity with no nuclear waste [3]. Integrated smart grid capabilities both in distribution and consumption can ensure that nuclear microgrids would manage the ebb and flow of demand and production far more efficiently than today's power generation infrastructure [3].

While there are major costs, regulatory issues, permitting and construction delays associated with large nuclear reactors, perhaps these hurdles might be overcome with smaller versions of nuclear technology. While fusion reactor demonstration projects in the U.S. are likely decades away, smaller nuclear reactors are more likely to become available. However, Integral Molten Salt Reactor (IMSR) technology is a small-scale and modular technology that is being explored by a Canadian company located in Ottawa. The IMSR uses molten salt as both the fuel and the coolant and operates on a variety of nuclear fuels including spent nuclear waste [4].

IMSRs can work in combination with renewable energy facilities such as solar and wind to produce continuous utility-grade, fossil-fuel free energy with no carbon footprint [4]. IMSR plants can also operate under ambient pressures making them much safer than conventional nuclear plants. They are not subject to the potential of radioactive gas explosions and there is no risk of meltdown upon failure [4].

With these advantages and the need to reduce greenhouse gas emissions on a world scale, is it time to consider package nuclear power plants for electrical generation? Possibly, yet there are high costs for the development of package nuclear energy systems and unresolved environmental concerns. Regulatory structures are not in place to enable wider application of package nuclear systems. The availability and comparatively lower cost of natural gas and renewables such as wind power and hydropower currently make nuclear power stations a more expensive option. Many renewable energy technologies are proven, scalable and have lower development costs. There are also fewer permitting obstacles. They remain the more cost-effective solutions to providing electricity with clean energy resources.

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Louisville, Kentucky

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Microgrid Architecture

Stephen A. Roosa, Ph.D., CEM, REP

FEATURES OF MICROGRID ARCHITECTURE

The critical infrastructures of today's modern world rely on having dependable electricity supplied continuously. Microgrid designers develop system architecture that attempts to achieve improved scalability, flexibility and security. The basic architecture of a microgrid includes generation, critical and non-critical electrical loads, a central controller, power interfaces, a point of common coupling and storage technologies. Digital systems manage interoperable distributive control functions and capabilities. The supportive architecture for microgrids has the elusive goals of ultimately providing component plug-and-play functionality, two-way electrical power transfer, and seamless connectivity with the utility grid. This article considers the features of microgrid architecture, their primary components, considers advanced microgrids and reviews microgrid regulations and standards.

Microgrid Operational Configurations

Microgrids are configured as substructures of the *macrogrid* that are comprised of local low-voltage and medium-voltage distribution systems with distributed energy resources (DER) and storage devices that satisfy the demands of energy consumers [1]. These systems can be operated in a *semi-autonomous* way, if interconnected to the grid, or in an *autonomous* way (islanding mode) if disconnected from the main grid [1]. Islanding capabilities are a fundamental feature of many microgrids. Intentional islanding is the act of physically disconnecting a set of electric circuits from a utility system, and operating those circuits independently [2]. *Anti-islanding* refers to safety protocols to prevent DERs from feeding power onto utility distribution networks during system outages [2]. These are designed to prevent harm to workers and damage to the grid during outages and power restoration efforts.

There are several basic components of the architecture of a microgrid that are fundamental. Most importantly, microgrids must contain the equipment necessary to generate electricity to satisfy loads. Microgrids usually have a form of energy storage system which does not necessarily need to be internal system. It may be configured to allow the host electric grid, if interconnected to serve as the primary electricity storage system. Within the microgrid there must be a set of electricity-consuming devices that dictate the loads placed on the microgrid. Examples include lighting systems, electric motors and fans, heating and air conditioning equipment, refrigeration systems, water heating, etc.—all typically associated with buildings. Automatic control systems may be used to enable selected loads to be cycled or shed during periods of peak electrical demand to optimize load management. Finally, grid-connected microgrids require a utility interconnection to enable the microgrid to exchange power with the larger utility network. If a microgrid is designed to operate only independently in island mode, then the utility interconnection with the macrogrid is not required.

The various generation components and auxiliary equipment of microgrids can present design problems when planning microgrid architecture. Often, multiple types of electrical generation systems are not initially designed nor configured to operate in concert with other systems. Regardless of microgrid configuration, to achieve the goal of providing resilient electrical power when needed, microgrids must be designed and constructed to ensure safe and seamless interoperability among the various electrical generation sources and any connected electrical storage equipment.

There are three conceptual configurations for electrical utility distribution systems: centralized, decentralized and distributed (see Figure 1). Centralized systems are a simple connection of nodes to a central point of electrical production. This is common in a utility configuration in which there is only one central power plant and transmission links and connections carry electricity from the plant directly to individual users (loads). The central plant provides continuous power by having multiple generators. However, a breakdown of the configuration at its central station may cause the entire system to fail. Decentralized configurations have multiple points of electrical generation which connect to their direct loads but also connect to either a central station or a number of remote stations. Decentralized configurations tend to have greater resiliency than centralized systems. Distributed configurations provide both generation and loads at each node and are linked to all other generation and load points in a web-like configuration. Distributed networks are the most resilient since a breakdown that occurs at any station or link can be resolved by rerouting transmission to ensure reliability.

Microgrids typically use either decentralized or distributed network configurations. By using a multi-resource model as a solution to the problem of electrictrification, a diverse portfolio of production options improves system redundancy to reinforce the power grid if a single electrical generating asset or resource is compromised [3]. Distributed configurations are most resilient for situations when single transmission pathways or specific nodes are compromised.

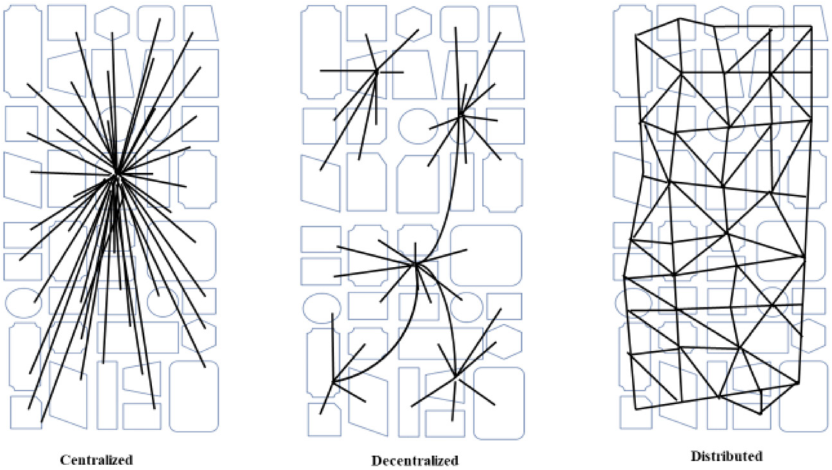

Figure 1. Centralized, decentralized and distributed network configurations. Source: Concept adapted from Baran, P., RAND Institute (1964).

Planning for Electrical Distribution Systems

There is an evolution in the development of electrical supply systems from central grid systems to smaller more resilient decentralized systems. From the utility's planning perspective, the aging of grid infrastructure increases the need for future upgrades and spawns rate increases. Electric utility companies, especially those with regulated service areas, may profit from the development of the improvements plus finance the costs by increasing the tariffs paid by their customers. Some electric customers, dissatisfied with the increasing costs and declining services of their utility supplier are generating their own power and using the grid-supplied power for backup purposes [4]. From the host utility's perspective, this arrangement may not be profitable since additional capacity must be available on short notice if the customer requires additional power. Some respond by increases in fees or fixed rates for access.

Implementing grid-related improvements is not only expensive but also creates service interruptions and major inconveniences. In November 2018, an emergency transmission line replacement over a major interstate highway in Kentucky was scheduled as a two-hour event but instead required an entire day, creating a traffic jam over 15 miles (24.1 km) long and leaving commuters stranded on remote sections of the highway for hours. In such instances, those impacted by the utility's decisions are not forewarned and receive no compensation for their lost time or expenses.

Planning at the building scale usually focuses on the building itself without consideration of capacity optimization. When a new skyscraper is constructed in an urban area, it is often assumed that the utility will simply have additional power on hand to meet the added loads. During the design process, many architects often have no idea of the building's estimated electrical usage nor have they attempted to calculate the building's electrical demand. This process often negates opportunities for load optimization and results in higher operating costs that are transferred to the owners. The building is plugged into the electric network and the hope is that the utility will have excess capacity for the long term.

Long-range electrical generation planning is capacity and transmission capability focused and often based on extension of regional demand projections. Building and system loads are considered to be beyond utility control. Planning at this scale often fails to account for the evolution away from central coal and nuclear plants that are being replaced by systems that generate electricity by renewable energy and natural gas sources [4]. Adjusting to intermittent resources and mixed fuel generation means that energy supply strategies must also adjust to be successful [4]. From the utility company perspective, meeting the requirements of dispersed electrical generation can be challenging.

Traditional electrical distribution systems provide a one-way transfer of electricity from the primary utility to their consumers. Some regional electric utility companies with regulated service territories behave as if they own the customers they serve and have sole rights to supplying power. When a microgrid is developed the question of who owns the customer becomes less clear. When customers are linked to the transmission system of the distributed energy resource developer, there can be two-way power flows between the DER and the local utility or power flow among and through DER developers. When effectively designed, system resiliency and reliability can be improved. For example, DER developers can supply power by orchestrating delivery from multiple developers through system interconnections to large numbers of consumers. Figure 2 shows local microgrid supply options for consumers linked to DERs.

Smart Grid Architecture

A proposed improvement to standard grid architecture is the smart grid model. The smart grid provides a set of functional categories that supports

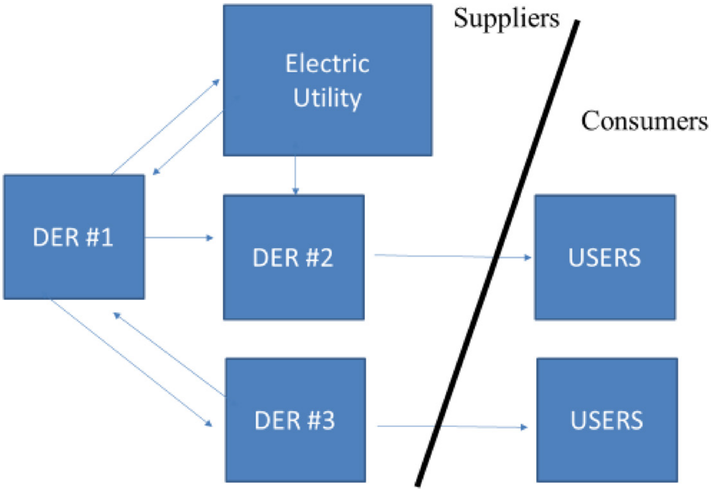

Figure 2. Local microgrid supply capability diagram for consumers using DERs as the primary electrical energy source.

a conceptual understanding of the grid frameworks. According to Eger et al., "From an architectural point of view the microgrid can be represented by selected viewpoints. Microgrid use cases can be decomposed into four interoperability layers modelling use case functions, information model and data requirements, communication and connectivity requirements and the components" [5]. The primary microgrid interoperability layers are:

Function layer: The function layer represents use cases, functions and services independent from their physical implementation in systems and components.

Information layer: The information layer describes the information related requirements, objects or data models which are required by the use cases, functions or services.

Communication layer: The communication layer describes all the communication and connectivity requirements.

Component layer: The component layer is the physical distribution of all participating components in the microgrid context. This includes power system equipment (typically located at process and field level), protection and control devices, network infrastructure and computer systems [5].

Smart grids are structured to optimize the use of technologies that provide automated, digital and intelligent, decision-making algorithms and data collected from sensors monitoring these components.

Alternative Architectures for AC and DC Microgrids

For microgrids, there are several types of basic architecture, divided into either alternating current (AC) or direct current (DC) networks. Efficiencies of the configuration will vary. Microgrid networks might include firm generation, electrical generation that is controllable and dispatchable such as a diesel generator, combined heat and power (CHP) generation or possibly battery storage [6].

The types of microgrid architecture vary in their efficiencies. Energy storage systems and firm generation types are dissimilar. The basic architecture of AC network configurations with solar photovoltaic (PV) used as the sample generation source include [6]:

AC network: The AC grid acts like a 100% efficient storage system, and the timing of the generation relative to the load is not critical.

AC microgrid + PV + battery storage: When generation and load are matched and there is no charging or discharging to and from the stage system, the energy flows and efficiencies are the same as in the AC network. In the disjoint case, the storage system absorbs all of the energy from the solar PV system and then delivers that energy to the aggregate internal loads at a later time. The use of storage to manage the net flow of power leads to losses as the batteries are charged and discharged [6].

AC microgrid with firm generation: Firm generation complicates the analysis of architecture efficiency since generator efficiency is a function of loading and speed. With AC architecture, the electrical losses are from the conversion of power from the AC bus to the DC internal loads assuming the generator is operated to handle loads [6].

The basic architecture of DC network configurations with solar PV used as the sample generation source include [6]:

DC network: The bidirectional inverter/converter imposes a round trip efficiency for exchanges with the AC grid.

DC microgrid + PV + battery storage: With storage system operation schemes similar to AC microgrids, similar logic can be applied to determine the efficiencies of a DC microgrid. In the matched case, the storage system is not charged or discharged, and the operation and efficiencies are the same as the DC network under during matched loads. In the disjoint case, the storage system absorbs all of the energy from the PV system and then delivers that energy to the aggregate DC internal loads as needed. Efficiency losses result [6].

DC microgrid with firm generation: Similar logic applies to the DC architecture, but the power from the generator passes through an AC-DC conversion process to get to the DC bus, and then can be used directly by 50% of the native DC loads at high voltage [6].

COMPONENTS OF MICROGRIDS

There are primary components of microgrids which are keys to the design of their architecture. Microgrids are configured based on the need to link and manage power generation sources with connected loads to meet selected goals. Enabled by intelligent control technology, microgrids manage the operation of all linked DERs while connected to the utility grid or being utilized as an independent power system [7].

Power Sources

Microgrids use distributed energy resources to generate electrical power. DERs are comprised of electrical generation and storage systems and can be deployed in a large number of units [9]. They have a number of common features: 1) they are not centrally planned; 2) they are often owned and operated by an independent power producer; 3) their power is not centrally dispatched; 4) they are interconnected to the central electric power system at any convenient point in the grid; 5) when operating connected to the grid, they may modify grid operation; and 6) the power supplied can be either dispatchable or non-dispatchable depending on the configuration [9].

Microgrids can be powered by distributed fossil-fuel generators, batteries, or renewable resources like solar panels and wind turbine generators [10]. Note that batteries when discharging are seen by the system as a source of power generation.

Microgeneration is the electricity generated by homes and small business that is distributed locally [11]. Despite the granular nature of the generation, the contribution from microgeneration sources in total makes a substantial impact. In the UK, renewable energy sources account for one-third of all electricity, and microgeneration accounts for 17% of the total [11]. For example, on 8 December 2019, the UK generated 16.2 GW of total electricity from wind which accounted for 43.7% of its electricity requirement. On that same day, biomass provided an additional 7.9% of total generation. While renewables accounted for 51.6% of the total electricity needed coal supplied only 3.1%.

An advantage of microgrid design is the ability to select from a number of generation sources, often in complementary combinations. The goal is to maximize electrical generation based on the resources available, their efficiencies and costs. As efficiencies improve, cost savings often result. An electric power plant's *efficiency* (η) is the ratio between the useful electricity output from the generating unit, in a specific time, and the energy value of the energy source supplied to the unit in the same time period [12]. The theoretical efficiency of converting various energy sources into useful electrical energy using a sampling of generation technologies is shown in Table 1 [12]. A secondary goal may be to reduce greenhouse gas emissions (GHG). This is accomplished by efficiency improvements but may be accomplished by energy conservation, fuel substitution, or using renewable energy resources. For example, system electrical generation efficiencies can be improved and greenhouse gas emissions reductions will occur by substituting hydropower generation or tidal power rather than using coal or natural gas.

Point of Common Coupling

A microgrid connects to the electric grid at a point of common coupling (PCC), the interconnection that maintains microgrid voltage at the same level as the grid unless there is a problem on the grid or other reason to disconnect [10]. The PCC is the location in the electrical system where multiple customers or multiple electrical loads may be connected [13]. It is the point of a power supply network, electrically nearest to a particular load, at which other loads are, or may be, connected [14]. These loads can be devices, equipment or systems, or distinct customer installations [14].

The PCC enables the transfer and exchange of electricity from the microgrid to the larger utility grid. When it is the point of coupling between the microgrid and the host electrical utility, IEEE-519 (a set of guidelines to measure power harmonics on power system connections between a utility line and a building) suggests that this be a point which is accessible to both the utility and the customer to enable direct measurement [13]. The PCC's primary job is to ensure that voltage regulation from the generation system is synchronized with the voltage from the main power grid. If the grid goes down, it must activate a circuit breaker that isolates the grid. To reconnect, the microgrid requires information about the grid power conditions, such as the frequency and voltage of the grid power. Usually, reconnection is possible within 10 seconds or less.

Microgrid Power Management Systems

The power management system handles the transfer of electrical power from the power source to the electricity consuming devices [15]. These types of electric load management usually require converting the electricity generated

Table 1.
Approximate electrical generation efficiencies of selected technologies.

Renewable generation systems	*Efficiency (%)*	*Fossil fuel generation systems*	*Efficiency (%)*	*Other generation systems*	*Efficiency (%)*
Hydro electric		Nuclear Fission	35	Municiple waste	28
Large hydropower	85-98	Natural Gas Turbine	38-42	Sterling engine	38
Small hydropower	25-90	Coal	32-42	Microturbines	20-30
Tidal power	90	Oil	42		
Ocean thermal energy conversion	4	Internal combustion engines			
Wind turbine generators	30-45	Petrol	25		
Solar		Diesel	35-42		
Thermal	25				
Photvoltaic	15-23				
Biomass	25-35				
Geothermal	10-12				
Fuel cells					
Solid oxide	48				
Phosphoric acid	40-45				
Melted carbonate	50				
Proton exchange	40				

from the power source with an inverter that transforms the electricity to the form required for most loads and interfaces with the microgrid's storage components to balance the electrical supply and demand loads [15]. The reliability and maintainability of digital control system components must be considered as the power management system provides critical services for the operation of the microgrid. The ultimate goal is to create a microgrid control system that provides balancing (see Figure 3), energy services and active control for energy-consuming devices that are deployed in smart buildings, residential areas, transportation systems and communities.

The control of the power flow in a microgrid is performed by operation algorithms implemented in the central controller which may utilize weather forecasts and other data [16]. Central controller reference values are distributed to the local power electronic converters whose control loops and topologies are adapted to microgrid requirements [16]. Special tasks for distributed control systems include stability assurance within the grid and active filtering [16]. Modern microgrid systems often integrate software and control systems, such as smart meters, that can manage the grid operation in an efficient and reliable manner [15].

Categories of Loads

Important microgrid components include electricity-consuming devices whose energy is supplied from the overall microgrid system [15]. Loads can be divided into groups based on the need for electricity. They are commonly categorized as sensitive, adjustable or shedable (see Figure 4). Tier 1 loads (sensitive) are those that must operate continuously without fail. These might include elevators, refrigeration equipment and emergency lighting. Tier 2 loads are discretionary (adjustable) and may be shifted or shed for a short term to balance generation availability. Examples include domestic water heating systems, certain fans and air conditioning loads. Tier 3 loads are those that can be shed for emergency operations due to unplanned and partial loss of generation. Depending on the actual loads, these might include kitchen equipment, interior lighting and emergency generation equipment. Some loads may fall into different tiers based on the season, time of day, or other considerations.

Energy Storage System

For many microgrids, batteries are a common type of energy storage technology. They can be designed to convert, store, manage and recycle energy for extended periods of time.

Figure 3. Microgrid control system to provide active balancing.

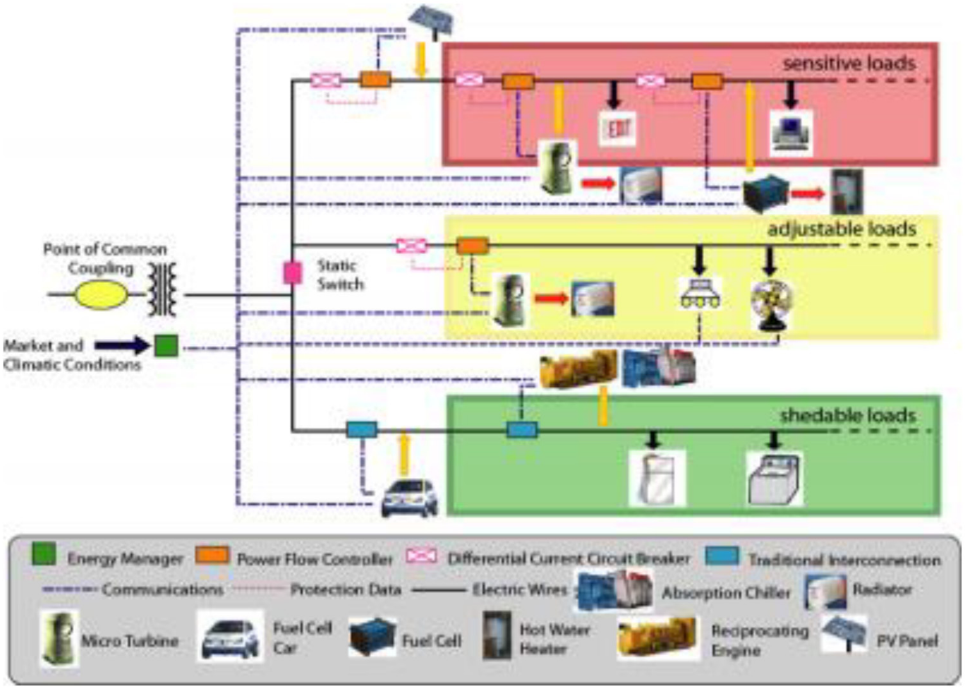

Figure 4. Graphic showing point of common coupling and types of loads. Source: Berkeley Lab [20].

There are microgrid applications of energy storage technologies which provide brief bursts of power. Ultracapacitor energy storage delivers power services with short response time (cycles ranging from milliseconds to minutes in duration) [7]. When combined with other storage technology, storage times can be extended to several hours. Ultracapacitors are high peak current devices with 100% depth of discharge capability which provide a significant reduction in the charge-discharge rate on the battery, which leads to longer battery lifetime [7]. Flywheels can provide bursts of electricity for periods of 5 to 30 minutes.

To ensure the lifecycle and safe operation of the batteries, more complex energy storage systems are equipped with a battery management system (BMS) to monitor and control the charge and discharge processes of the battery's cells or modules [8]. The configuration for the internal control architecture for a basic BMS would include direct connections from the BMS to the storage controller and the batteries with both also connected directly to a converter. To be fully functional, this configuration further requires an electrical connection and communication to external generation and systems. The control scheme should in turn be determined by the application, which establishes the algorithmic and input/output requirements for the electrical energy storage system (see Figure 5) [8].

ADVANCED MICROGRIDS

Advanced microgrids are a sub-category of microgrids with defined characteristics, some similar to conventional definitions of microgrids with enhanced capabilities that enable the microgrid to offer improved services. According to researchers at Sandia National Laboratories [17], the defining characteristics and features of an advanced microgrid include:

1) Being geographically delimited or enclosed.
2) Having a connection to the main utility grid at one PCC.
3) Being fed from a single substation.
4) Capable of automatically transiting to and from the grid and operated in island mode.
    — operates in a synchronized and/or current-sourced mode when utility-interconnected.
    — is compatible with system protection devices and coordination.
5) Includes DER, but generator agnostic and in accord with the needs of customer with renewables (inverter interfaced), fossil fuel based (rotating

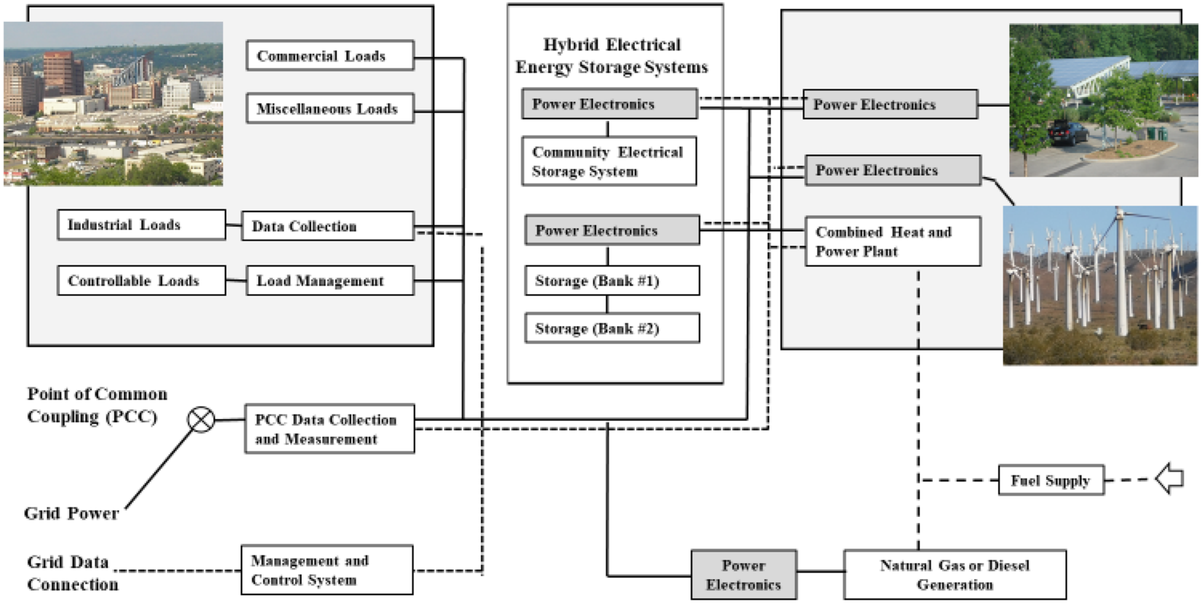

Figure 5. Microgrid architecture for small to medium size enterprise (source: concept adapted from Paderborn University [16]).

equipment generators) and/or integrated energy storage.

6) Includes an energy management system (EMS) with controls for power exchanges, generation, load, storage, and demand response and load-management controls to quickly balance supply and demand.
7) Includes real time and instantaneous power and information exchanges across the PCC [17].

Meeting these requirements directly impacts microgrid system architecture by integrating new controls, energy storage and renewable energy systems to enable greater cost savings and environmental benefits. They achieve plug-and-play interoperability by using sophisticated technologies and digital controls that enable peer-to-peer, autonomous coordination among micro-sources [19]. Advanced microgrids typically use inverters and controllers to interface with the EMS or other coupled microgrids [17]. Inverters can provide multiple functions to enable smart-grid interoperability. A challenge for microgrid applications is that the technologies deployed need to address the optimal mix of power flow [17]. Networked hybrid designs for microgrids may prove to be the optimal configuration to maximize efficiency and performance [17].

With such capabilities, microgrid owners have the capability with advanced microgrids to optimally manage system resources to address threats and potential consequences, and respond to quickly to changes in priorities [17].

MICROGRID REGULATIONS AND STANDARDS

Microgrid architecture is strongly influenced by regulations and standards. There is a long history in the electrical utility business of maintaining monopoly status, influencing both regulations and their enforcement procedures. They often view non-regulated power generation as a threat which increases their business risks. The paradox is that rather than increasing risks, microgrids when properly designed can actually reduce risks and grid instabilities. Much of the regulation that applies to U.S. microgrid interconnections is created by the state governments, not by the federal government [18]. Regardless, once regulations are established, maintaining compliance is a chief concern for both public utilities and microgrid operators.

There are understandable concerns about microgrid regulation regardless of the type or configuration of electrical generation systems—especially those that are independent of utility grids. Regulatory policies simply have not been adopted that are congruent with the vision of the utility system provided by the introduction of microgrids. Microgrids regardless of the architecture employed encroach on many areas of existing regulation not conceived prior to their recent popularity (i.e., generator interconnection rules, air quality permitting, building codes, tariffs, etc.) [18]. A fundamental example: traditional interconnection rules often require microgrid generators to disconnect when disturbances in the grid occur, though one of the objectives of microgrid development is to achieve systems that can island and fully or partially ride through grid-induced problems [18]. However, the regulatory environment concerning microgrids is in flux and there a number of recently adopted or updated regulations and standards.

U.S. Clean Air Act

The Clean Air Act is the law that defines U.S. Environmental Protection Agency (EPA) responsibilities for protecting and improving the nation's air quality and the stratospheric ozone layer [21]. The EPA establishes requirements on the use of fossil fuel generation systems which are enforced by state and local governments. Microgrids using fossil fuels must comply with its provisions (see https://www.epa.gov/clean-air-act-overview). Of greatest concern for microgrids is Title I of the Act which covers air pollution and control. Its parts identify requirements for air quality and emission limitations, ozone protection, preventing significant deterioration of air quality and requirements for nonattainment zones. Title III covers general provisions including administration, licensing, economic impact analysis and exemptions. Title V identifies permitting requirements.

U.S. greenhouse gas regulations and policies are limited. In April 2009, the EPA released a proposed finding on CO_2 and five additional GHGs (methane, nitrous oxide, hydrofluorocarbons, perfluorocarbons and sulfur hexafluoride). The agency stated that "in both magnitude and probability, climate change is an enormous problem" and that GHGs "endanger public health and welfare within the meaning of the Clean Air Act" [22]. It cited man-made pollution as a "compelling and overwhelming" cause of global warming. According to EPA administrator Lisa Jackson, the finding "confirms that GHG pollution is a serious problem now and for future generations." On April 2, 2007, the U.S. Supreme Court ruled in *Massachusetts v. EPA* that carbon dioxide could be regulated as a pollutant under the Clean Air Act and that the government had a responsibility to issue a determination based on science. The Bush administration failed to act on this ruling. This finding was prompted by a Supreme Court decision in April 2007 ruling that GHGs are indeed pollutants as classified by the Clean Air Act and regulation is required if human health is threatened [23]. Most federal government programs regarding GHGs languish or are being unenforced or dismantled as a result of administrative policy changes beginning in 2016 under the present administration. Regardless of the failure of recent federal governmental leadership, individual U.S. states are making impressive policy gains in efforts to reduce GHG emissions (e.g., New York, Connecticut and California).

U.S. Public Utility Regulatory Policies Act (PURPA)

The PURPA was enacted in 1978 as part of the National Energy Act and amended as part of the Energy Policy Act of 2005. It is the only federal legislation requiring competition in the utility industry. It effected the development of alternative energy and co-generation production by requiring public utilities to purchase power produced by co-generators at reasonable buy-back rates, typically based on the utility company's cost [24]. This effectively created a market for non-utility power producers. PURPA guaranteed that the cogeneration or small power producer would be able to interconnect with the electric grid and access backup services from the utility [24]. It also exempted cogenerators and small power producers from federal and state utility regulations and associated reporting requirements of these bodies [24]. The portion of the act dealing with cogeneration and small power production appears in U.S. code in Title 16—Conservation, chapter 12—Federal Regulation and Development of Power, subchapter II—Regulation of Electric Utility Companies Engaged in Interstate Commerce, section 824a-3—Cogeneration and Small Power Production [25].

To assure the benefits of PURPA, a cogeneration facility had to be classified as a qualifying facility, generating electricity and useful thermal energy from a single fuel source [24]. In addition, a qualified cogeneration facility had to be less than 50% owned by an electric utility or an electric utility holding company [24]. Finally, the plant had to meet the minimum annual operating efficiency standards established by the Federal Energy Regulatory Commission (FERC) when using oil or natural gas as the principal fuel source [24]. The minimum efficiency standard established was that the useful electric power output, plus one half of the useful thermal output of the facility must be either: 1) no less than 42.5% of the total oil or natural gas energy input; or 2) 45% if the useful thermal energy is less than 15% of the total energy output of the plant [24].

PURPA is becoming less important as many older supply contracts expire and electric deregulation and open access to electricity transportation by utilities has created a vast market for the purchase of energy [25]. Though PURPA was amended under the Energy Policy Act of 2005 to allow the

Federal Energy Regulatory Commission (FERC) to exempt utilities from its requirements if qualifying facilities are provided access to wholesale markets, it has not been updated to reflect the advent of microgrids and need for more competitive markets [26]. In fact, many state regulatory agencies have stopped requiring utilities to offer contracts to developers of non-utility power projects [25]. Regardless, PURPA remains important as it promotes renewable energy (especially hydropower) by exempting the developers of such projects from onerous state and federal regulatory regimes [25].

In 2018, the National Association of Regulatory Utility Commissioners (NARUC) promoted that PURPA be updated for the energy sector [25]. NARUC is proposing that the FERC "exempt from PURPA's mandatory purchase obligation those utilities which are subject to state competitive solicitation requirements and other best practices that ensure all technologies access to the market" [26]. Citing examples that qualifying facilities have invoked PURPA in an anti-competitive manner, NARUC suggested that reforms would better enable competitive solicitation and procurement [26].

IEEE Standard 1547-2018 for Interconnection and Interoperability of Distributed Energy Resources with Associated Electric Power Systems Interfaces

Institute of Electrical and Electronics Engineers (IEEE) Standard 1547-2018 outlines the requirements and technical specifications for interconnecting distributed resources safely with the grid. This includes design, safety, response to abnormal conditions, power quality, equipment, production, installation, commissioning and periodic testing [27]. This standard was first published in 2003, after five years of development, with the goal of creating a set of technical requirements that could be used by all parties on a national basis [28]. It also addresses unintentional islanding by requiring detection of the island condition and the ability to cease to energize the area electric power system (EPS) within two seconds of the microgrid's island formation [28]. It emphasizes installation of DER on radial primary and secondary distribution systems using 60 Hz sources. IEEE 1547 also provides anti-islanding standards to protect the safety of utility line workers [2].

IEEE P1547.4-2011 Guide for Design, Operation, and Integration of Distributed Resource Island Systems with Electric Power Systems

Intended for use by designers, operators, system integrators, and equipment manufacturers, IEEE P1547.4 covers microgrids and intentional islands that contain distributed resources connected at a facility and with the local utility [28]. The guide covers the distributed resource, interconnection systems, and participating electric power systems [28]. It provides alternative approaches and good practices for the design, operation, and integration of microgrids and covers the ability to separate from and reconnect to the utility grid while providing power to the islanded local power systems [28]. It is relevant to the design, operation, and integration of distributed resource island systems [29]. Implementation expands the benefits of using distributed resources by targeting improved reliability and builds upon the interconnection requirements of IEEE Standard 1547(TM)-2008 [29].

IEEE P2030.7-2007 IEEE Standard for the Specification of Microgrid Controllers

Microgrid controllers are direct digital control (DDC) systems that are responsible for managing the operating equipment within the microgrid. A key element of microgrid operation is the microgrid energy management system (MEMS). IEEE P2030.7-2007 is an international standard that defines how microgrid control functions operate as self-managing, autonomous, or grid connected, and seamlessly connect to and disconnect from the main distribution grid for the exchange of power and the supply of ancillary services [30]. The standard categorizes microgrid functional control assignments into four blocks: grid interactive control functions, supervisory control functions, local area control functions, and device level control functions [31].

The scope of this standard is to address the functions above the component control level associated with the proper operation of the MEMS that are common to all microgrids, regardless of topology, configuration or jurisdiction [30]. It also describes control approaches required from the distribution system operator and the microgrid operator [31]. IEEE Standard P2030.7-20078 addresses testing procedures and attempts to ensure interoperability of the microgrid by defining which parts of the microgrid controller must be standardized and which can remain proprietary [27].

IEC 61727 International Electrotechnical Commission's PV System Requirements

This international standard applies to utility-interconnected solar photovoltaic power systems operating in parallel with the utility and utilizing static (solid-state) non-islanding inverters for the conversion of DC to AC power. It describes the international requirements for photovoltaic systems interconnecting with existing or proposed low-voltage utility distribution systems. Recent updates provide clarification regarding for non-islanding inverters, point-of-common coupling and power factor.

Microgrid Standards Being Developed [25]

IEC TS 62898-1—Guidelines for microgrid projects planning and specification, published
IEC TS 62898-2—Microgrids Guidelines for Operation, working document
IEC TS 62898-3-1 Microgrids—Technical/protection Requirements, working document
IEEE P1547 REV—Microgrid Connection to Distribution Utilities; Microgrid/ Distribution Utility, ISO/RTO
IEEE P157.8/D5.0—Draft Recommended Practice for Establishing Methods and Procedures that Provide Supplemental Support for Implementation Strategies for Expanded Use of IEEE 1547 (Clause 8- Recommended Practice for DR Islanded Systems)
IEEE P2030.10—Standard for DC Microgrids for Rural and Remote Electricity Access Applications
IEEE P2030.9—Recommended Practice for the Planning and Design of the Microgrid
IEEE P2030.7—Standard for the Specification of Microgrid Controllers
IEEE P2030.8—Standard for the Testing of Microgrid Controllers

SUMMARY

Microgrid architecture is normally configured as either a decentralized or distributed network. While there are basic components fundamental to the architecture of a microgrid, the microgrid must contain the equipment necessary to generate electricity. They may also have a management system, loads, and possibly storage capabilities. Microgrids can be designed to completely grid-independent or connected and capable of operating in island mode. Unlike traditional electrical distribution systems, microgrids are often configured to provide bidirectional transfer of electricity, either from the host grid to the microgrid or from the microgrid to the grid. They can be designed to use AC or DC power or both. A proposed improvement to standard grid architecture is the smart grid which functionally supports a conceptual understanding the electric grid's framework. Microgrids designs can reinforce the configuration and goals of smart grids.

A feature of microgrids capable of islanding is the point-of-common interconnection between the microgrid and its host grid. Advanced microgrids are a sub-category of microgrids with defined characteristics, some similar to conventional microgrids but having supplemental capabilities that enable them to provide improved services for their customers. Toward the goals of maximizing electrical generation based on resource availability, production efficiencies and costs, microgrid operators can select from a number of complementary combinations of generation sources.

Microgrid architecture is influenced by the regulations that apply to their development. Those using fossil fuels must comply with the provisions of the U.S. Clean Air Act, primarily Title I of the Act which sets standards for air pollution. The IEEE has established standards for microgrid interconnection requirements and provides microgrid design, operation and interconnection guidelines. Other microgrid standards are evolving. Microgrids create a special regulatory issue as many U.S. states and local governments have not yet adopted regulations for their design and implementation. However, many have regulations concerning the development of distributed energy resources and guidelines concerning utility interconnections.

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Sharing Best Renewable Energy Practices In the Developing World

Nancy L. Najarian

ABSTRACT

Increasing the use of renewable energy and energy efficiency in developing countries is critical to combating climate change and improving the lives of residents. An array of tools, online and in print, are available to these countries to assist with project preparation and management. The ultimate objective is to help countries and their citizens achieve carbon reduction goals set on a national or community level. *Are these tools and technical assistance being accessed as fully as intended?* Asking and answering the following questions will help determine if and how these tools are being applied by countries, leadership, businesses and residents to share lessons learned and best practices. The answers to these questions also helps ascertain if sharing information between these entities is enabling measurable increases in the use of renewable energy and energy efficiency practices. 1) Are lessons learned and best practices being shared effectively? 2) Can those in remote villages find out what worked thousands of kilometers away? 3) What tools are available to a developer interested in privately funding a project? Can data and lessons learned be freely shared in the private sector? 4) What can energy professionals do to provide needed expertise and best practices to the developing world? 5) What lessons can the U.S. learn from activities in the developing world?

INTRODUCTION

With increasing urgency, developing countries are responding to the need to reduce carbon emissions (CO_2e) by developing renewable energy and practicing conservation by implementing energy efficiency measures. They provide electricity using renewables to regions that previously had not enjoyed reliable sources of energy. According to data released in April 2019 by the International Renewable Energy Agency (IRENA), a decade-long trend of strong growth in renewable energy capacity continued in 2018 with global additions of 171 gigawatts (GW) in electrical capacity. This 7.9% annual increase was due primarily to new additions of wind and solar energy—totaling 84% of the growth. One-third of global power capacity is now based on renewable energy, and nearly two-thirds of all new power generation capacity added in 2018 was from renewables, led by emerging and developing economies [1].

Table 1. 2018 Renewable generation capacity by region [1].

Region	*Capacity (GW)*	*Global Share (%)*	*Change (GW)*	*Growth (% increase)*
Asia	1,024	44	105.0	11.4
Europe	536	23	24.0	4.6
North America	366	16	19.0	1.4
South America	211	9	9.4	4.7
Eurasia	100	4	4.1	4.3
Africa	46	2	3.6	8.4
Oceania	32	4	1.8	17.7
Middle East	20	1	1.3	7.1
Central America and Caribbean	15	1	0.8	1.5

According to IRENA and the United Nations (UN) in a recent report, “Renewable energy deployment needs to grow even faster, to ensure that we can achieve the sustainable development goals” [1,2].

What has impacted the growth in renewable energy in the developing world, and how can this growth be accelerated?

Development financial institutions (DFI’s) such as the International Finance Corporation (IFC) of the World Bank Group, the Asian Development Bank (ADB) or the U.S. Development Finance Corporation (DFC) provide financial resources for energy projects [3]. Often simultaneously, government-to-government technical assistance is provided to build the capacities of organizations and individuals who operate and expand their use of renewable energy.

Table 2. Enabling measures to increase renewable energy use.

State policy
Public utility and national outreach coordinators
Capacity building
Organized civil society
Financial institutions and investors

Many tools are available to assist these countries with project preparation and implementation. These tools include: national, regional or global studies and maps locating sites favorable to develop wind or solar farms; free software tools that help analyze the economics of a particular type of renewable energy; and workshops that connect policy makers and implementers and provide them with a forum in which to share their experiences and best practices. The ultimate goal is to help countries and their citizens achieve carbon reduction goals set on a national or community level.

Are countries, leaders, and stakeholders utilizing the lessons learned by others and best practices to deploy and/or improve their use of renewable energy in their own countries? A recent study funded by the National Renewable Energy Laboratory (NREL), emphatically underscored the value of countries sharing their experiences [4]. Any country's ability to successfully integrate variable renewable energy depends on many factors including technical requirements, resource options, planning processes, market rules, policies and regulations, institutional and human capacity, and what is happening in neighboring countries. The more diverse and robust the experience base from which a country can draw, the more likely that it will be able to implement an appropriate, optimized, and system-wide approach. This is as true for countries in the early stages of renewable energy integration as it is for countries that have already had substantial success. Going forward, successful renewable energy integration will depend upon the ability to maintain a broad ecosystem perspective, to organize and make available the wealth of experiences, and to ensure that there are pathways from analysis to enactment [4].

How are these tools and technical assistance being accessed, and is their impact sufficient to make the dramatic changes our world needs to combat climate change? Are the lessons learned and best practices being effectively shared? International, regional and national organizations provide data, expertise, and support to guide governments as they connect with their private sectors, individuals and communities, and make a commitment to reduce greenhouse gas emissions (GHG) with the use of renewable energy and related energy efficiency.

It Begins with Vision and Leadership

An enabling environment is necessary to move a country toward increased renewable energy usage, and a multitude of organizations assist governments with creating this environment. As has been demonstrated across the developing world and industrialized nations, a strong leader who provides a vision for moving the country toward carbon reduction is important. Leadership sets the goals and builds excitement within their populace and stakeholders who form coalitions that commit to low CO_2e energy sources. The coalitions determine what is needed and how to go about creating an enabling environment. Ultimately the leadership's goal is to facilitate policies, create programs and foster an environment that offers inviting business opportunities for investment in new renewable energy projects. The countries of Costa Rica, Uruguay and India provide examples of how leadership and policy support transformed individual developing countries.

COSTA RICA

Costa Rica, a country of 4.8 million, has produced many leaders who promoted and acted upon commitments to combat climate change with progressive environmental policies at home and internationally [5].

- 2007—President Oscar Arias Sanchez announced that his country would mark the bicentenary of its independence from Spain in 2021 by becoming carbon neutral.
- 2012—The 1st Country Carbon Program Neutrality 1.0 was launched with a national strategy and an action plan: it encouraged private companies to adopt practices to reduce their emissions and compensate for their carbon footprint.
- 2015—Costa Rica generated 99% of its electricity from renewable sources—80% from hydropower and 11.5% from wind generation. (Costa Rica and its rapid transition to renewable energy were helped by substantial amounts of rainfall in 2014/15, and the subsequent increase in the potential of hydropower in the country.)
- 2017—for 300 days the country's grid operated on 100% renewable energy.
- 2018—Costa Rica passed a law to promote electric vehicles (EVs) through improved access to credit and economic incentives, setting the stage to decarbonize the transportation sector.
- 2019—Current President Carlos Alvarado unveiled the detailed 2050 National Decarbonization Plan (NDP): a long-term roadmap for a transition away from fossil fuels and from more polluting ways of producing food and managing waste. The Environment Minister Carlos Manuel Rodríguez noted that if the plan is achieved, his grandchildren in 2035 will have the same carbon footprint as his grandparents in the 1940s. By 2050 his grandchildren will have none at all [5].

Costa Rica's Environmental Leadership

Costa Rica's leadership places great importance on the environment, and that includes the manner in which the government is organized. "When you have the ministries of energy and environment in the same house you can make big leaps forward. Same person, same agency," says Carlos Manuel Rodriguez, Minister of Environment and Energy for Costa Rica. Other examples include the role the leadership has shown both nationally and internationally. Former Costa Rican President José María Figueres served on United Nations Secretary General Ban Ki-moon's Advisory Group on Climate Change and Energy. Christiana Figueres, the Rodriguez's younger sister, led the UN Framework Convention on Climate Change, the group that convened the 2015 Paris climate agreement [5].

Costa Rica's Challenges

There is urgency and need to revolutionize Costa Rica's transportation system; half of the country's cars are more than two decades old and very polluting. Demand for cars is rising. More than 60% of the country commutes by diesel buses or trains, and transportation accounts for 60% of GHG emissions. Since 2002, there has been a moratorium on oil exploration and exploitation in the nation's continental and marine territories which is in effect until 2050 [5].

"This is the new Costa Rica... we know that the future is renewable and electric."

We have all the conditions—clean electricity, a young president who wants to do right, and technologies on our side. Renewable energy has become a part of the country's identity. People feel proud: they believe it's a Costa Rican thing to go green. The president knows that he can set a precedent at a time when the world is trying to figure out how to transition to electric mobility. We have to show that it's doable and beneficial, that it works technologically; I think that's the value of a small country doing it first. Monica Araya, Costa Rica Clean [6].

New Policies

Costa Rica's policy to decarbonize transportation and its National Decarbonization Plan focuses on:

- Having new electric passenger and freight trains by 2022.
- Nearly a third of all buses will be electric by 2035.
- Vehicle charging stations will be built.
- By 2050 nearly all cars and buses on the roads would be electric.

Costa Rica has become a leader among Latin American countries in electrifying the transportation sector. The nation's approaches provide a model which can be replicated across Central America [5].

Sharing Best Practices

To share best practices from Costa Rica's experience, the World Bank promotes high-level workshops, training programs and discussion of international best practices [7]. The project:

- Helps key decision makers strengthen their technical capabilities to launch electric public transportation initiatives for Costa Rica's cities.
- Offers valuable takeaways for countries in the region where the demand and support for clean transport systems is growing.
- Costa Rica's example holds important lessons for the rest of the world. It took a courageous stance based on the scientific evidence in 2007; and, it established a series of commitments to reduce CO_2e with ambitious goals that focused on the long-term avoidance of climate change. Their mission inspired people with a positive vision [5].

Lessons from Costa Rica for Rapid Transition to Renewable Energy

Finding the best pathway for a rapid transition to renewable energy involved Costa Rica working to take advantage of its unique resources and taking a strong leadership stance to attract investment.

- Policy, infrastructure, and cultural development need to happen concurrently to make rapid transitions.
- Countries with less historical responsibility for tackling climate change can show leadership and provide successful examples to other countries with greater culpability [5].

URUGUAY

In 2000, oil accounted for 27% of Uruguay's imports, a country with a population of 3.4 million. In 2002, a 218 km (135 mile) long pipeline was constructed that supplies natural gas from Argentina with an annual capacity of 1.8 billion m^3. At that time the country was heavily reliant of fossil fuels. In 2015 at the Paris Climate Talks, Uruguay's head of climate change policy (and former Environmental Minister) Ramón Méndez pledged an 88% cut in CO_2e by 2017, compared with the average for 2009 to 2010 [8]. Today, renewables provide 95% of the country's electricity and prices are lower than in the past relative to inflation. There are also fewer power outages because the country's diverse energy mix means greater resilience to outages due to droughts.

Attracting Investment

There have been no new nuclear nor hydroelectric power additions in Uruguay in over 20 years. According to Mendez, the keys to success are encouragingly replicable: "clear decision-making, a supportive regulatory environment and a strong partnership between the public and private sector. What we've learned is that renewables are financial business. The construction and maintenance costs are low, so as long as you give investors a secure environment, it is very attractive" [8].

Uruguay—Highlights of Renewable Energy Adoption

An important aspect of Uruguay's successful adoption of renewable energy has been the public and private sectors' ability to work together—with remarkable results. In addition, the government of Uruguay maintained a stable democracy and provided reliable partnerships with private companies. The following are highlights of Uruguay's adoption of renewable energy.

- From 2010 to 2015 energy investment in Uruguay, mostly for renewables, surged to $7 billion, or to 15% of the country's total annual gross domestic product, five times the average of Latin American countries.
- Given the area's reliable wind speeds (averaging 3.6 m/s or 8 mph), the state utility guarantees a fixed electric price for 20 years. Maintenance costs are low and stable, and investors are guaranteed a profit.
- A mix of renewables creates greater resiliency to climate change.
- A lower risk of electrical power disruptions exists because wind farms supply electricity to hydropower plants, thus reducing vulnerability to drought conditions by 70%. As a result, Uruguay no longer imports electricity and in 2014 exported a third of its electricity generation to Argentina [8].
- In March 2018 wind power became the principal source of electrical generation surpassing hydropower in contributing electricity to the national grid. According to the state electric company (UTE), wind power contributed 40.5% of total generation compared to hydropower's 38.4% [9]. Biomass (8.9%), thermoelectric (7.6%), solar power (4.6%) and imports contributed the remaining electricity [10].

Uruguay's Challenges

The country's challenges to meeting its renewable transition goals mainly involve transportation systems, a sector dependent on oil and derivatives that accounts for 45% of its energy use.

Electromobility program: launched in June 2018 this initiative promotes the transition towards electromobility, a sustainable and efficient urban transport

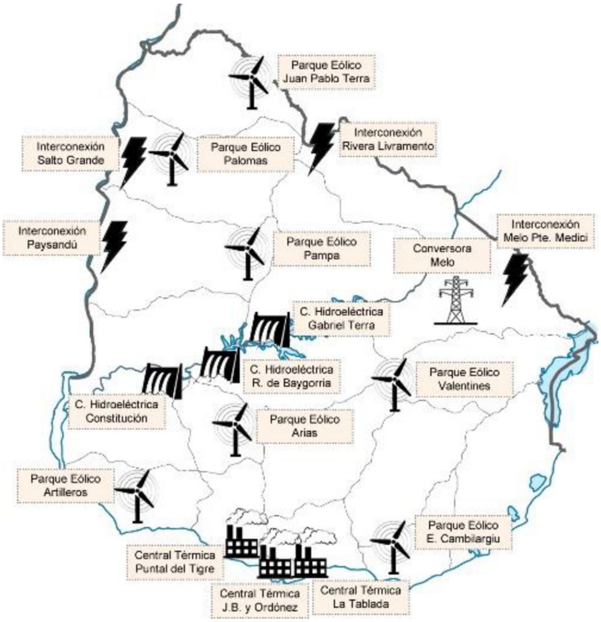

Figure 1. Power generation in Uruguay (source UTE [10]).

system. It begins in Montevideo's metropolitan area, moving on to other cities.

Program objectives: establish a regulatory framework for a low-carbon transportation system, promote the adoption of EVs for public transport and utility use, and foster cultural change [11].

Lessons Learned from Uruguay's Experience

Ramón Méndez attributed Uruguay's success to three key factors:

Credibility: a stable democracy that has never defaulted on its debts, making long-term investment attractive.

Helpful natural conditions: good wind, decent solar radiation and lots of biomass from agriculture.

Strong public companies: be a reliable partner for private firms who can work with the government to create an attractive operating environment [8].

Uruguay has proved that renewables can reduce electricity costs, meet well over 90% of electricity demand without the back-up of coal or nuclear power plants, and that the public and private sectors can work together effectively in this field." Ramón Méndez, Uruguay's head of climate change policy [8].

Strong Decision Making

The biggest lesson that Uruguay provides is the importance of strong central decision-making. Uruguay was once paralyzed by a seemingly endless and rancorous debate about energy policy. The government finally agreed to a long-term plan that drew cross-party support, ending the paralysis. "We had to go through a crisis to reach this point", Méndez said … "but in 2008, we launched a long-term energy policy that covered everything … Finally, we had clarity" [8].

INDIA

In 2008, 400 million people in India lacked access to electricity. In rural locations that where grid-connected, people were without power for 12 to 14 hours each day. Just 11 years later, India can be described as a leader in renewable energy deployment.

India's Development of Renewable Energy

In 1988, the United States Agency for International Development's (USAID's) and the Association of Energy Engineers (AEE) launched a series of workshops on energy efficiency and renewable energy in five of India's largest cities. Led by Dr. Stephen Roosa, the AEE representatives met with India's newly appointed Renewable Energy Secretary and helped outline ways to introduce renewable energy to India's remote locations that lacked electricity. These meetings and workshops were instrumental in launching a series of events that spawned India's governmental initiatives to promote renewable energy development in India. The 1992 Kyoto Protocol initiated its Clean Development Mechanism which enabled numerous Joint Implementation projects that supported solar power development in India. With the election of Barack Obama as president in 2008, the U.S. started a new partnership on energy between India and the U.S. By 2009, India and the U.S. launched a multi-pronged initiative called the Partnership to Advance Clean Energy (PACE) [12], the highlights of which included:

- A joint research and development (R&D) initiative that brought together scientists and industry from both countries, who worked on solar energy, building energy efficiency and biofuels.
- When Prime Minister Narendra Modi entered office in 2014, the cost of clean energy technologies declined due to technological innovation. Modi previously had worked at the state level experimenting with deployment of

new energy technologies and had written a book on climate change [12].

What Changed in India?

By 2015, during the UN climate negotiations in Paris, India and the U.S., plus 21 countries and the European Union pledged to double their investments in clean energy R&D. India's federal government at the time was only investing $72 million on clean energy R&D; as part of this coalition it served as the laboratory for many climate technology innovations [13].

- Policies that once seemed too progressive for India were embraced.
- India's original 2015 goal was to install 20 gigawatts (GW) of solar capacity by 2022; in 2018 this increased to 227 GW.
- A commitment was made to add renewable generation from wind and small hydro and to boost the nation from one that lacked adequate electricity to one with a surplus.
- The country announced the goal of obtaining a "100% national electric vehicle fleet" by 2030 [13].

Investment and Innovation

Though not everyone has access to electricity, rolling blackouts are no longer common. India's states have become centers of innovation. For example:

- The southern state of Karnataka recently became the first to endorse an official policy on EVs and battery storage. The policy enables the creation of a new battery storage innovation center, mandates charging infrastructure, and creates a program to train electric auto technicians.
- The eastern state of Odisha established a customer call center for people having issues with their rooftop solar installations to improve the quality of after sales support and maintenance [13].

India's Challenges

India's targets are to provide continuous electricity to all households by 2019 and improve the finances and efficiency of the state-owned utilities by integrating 175 gigawatts of new renewable energy onto the grid.

- With newly developed renewable energy resources, intermittency is a problem due to lack of sufficient electrical energy storage.
- India's states are grappling with building regional grid connections and installing smart meters to make electricity distribution more cost-efficient.
- To improve collection efficiency, India must solve the problems of rampant electricity theft and a political culture of subsidizing electricity for electoral gains.

- India's demand for coal rose by 9.1% to nearly one billion tons during the year ending in March 2019. Coal is one of the country's top five imports, with total imports rising from 166.9 million tons in 2013-2014 to 235.2 million tons in 2018-2019 [14]. This increase in demand is counter to India's efforts to reduce pollution and GHG emissions.

Lessons Learned from India

India has made substantial strides in moving toward the use of renewable energy. It is a model of a populous nation enacting policies, making investments, and carving a path toward meeting its Paris Climate Agreement Nationally Determined Contribution (NDC) goals. Taking further actions will help India aim for deeper reductions in CO_2e, exceeding current government targets [15]. Suggestions for policymakers that go beyond a sole focus on the renewable energy supply include:

Better frameworks for electricity: Production variability is the feature of certain types of renewable energy. This requires flexible grid infrastructure and custom contractual terms. Time of day pricing for electricity is an important first step. Today, only about 3% of electricity is purchased through exchanges that reflect supply and demand conditions; the balance is purchased through power purchase agreements that treat all power the same, regardless of its variability.

Worldwide 1.2 billion people lack access to electricity and spend large amounts of money on kerosene, candles and charcoal. Four million people die annually from indoor air pollution from these inefficient sources of energy and countless more remain locked in poverty [16].

Smart grids: Smart grids are more than just smart meters. The grid of the future will allow demand to react to variable renewable energy supply.

Energy efficiency: Energy efficiency needs more attention and funding. There is no regulated rate of return for efficiency investments. New buildings will be part of the capital stock for decades, but builders often disregard occupant energy costs. Lack of energy efficiency programs in the housing sector is a major gap.

Co-benefits: Greater market penetration of clean energy technologies, including EVs, will accelerate since they offer additional benefits, including energy security, employment, and reduced air pollution. These co-benefits need to be recognized during planning processes at the central, state, and municipal governmental levels.

Global support: An influx of global capital would increase funding and lower interest rates. India needs more than the transfer of current renewable energy technology; it also needs innovative regulation and business models. Global lessons learned can help [15].

Costa Rica, Uruguay, and India are examples of countries that benefitted from strong and visionary leadership which sparked substantial progress toward reducing CO_2e. The lessons learned and best practices from each country's experience are being shared globally and impacting other developing countries' leadership gains and policies.

CAN THOSE IN REMOTE VILLAGES LEARN WHAT WORKED IN SIMILAR COMMUNITIES, 1000'S OF KILOMETERS AWAY?

The challenge of sharing information across the world, be it from the most populated urban centers to the most remote of areas, is being met by organizations that choose a specific focus and offer lessons learned to benefit others. EarthSpark International is an example of a not-for-profit entity that works to bring electricity to remote areas and shares best practices including innovative technologies [16]. Their mission includes researching and developing business models that can be scaled to address energy poverty.

Figure 2. Town-sized, solar-powered smart grid in Les Anglais, Haiti, energized in 2012 [16].

Developing Innovative Technology and Transferring Business Models from South to North

EarthSpark believes that important innovation in decarbonizing the global energy supply may come from remote villages that lack electricity. The absence of incumbent infrastructure presents opportunities to build energy systems with today's best technologies and business models. These models leverage clean energy, storage, smart grid, and customer participation. They can be adapted elsewhere and inform evolving utility business models in established markets [16].

Smart Metering

EarthSpark built an innovative new infrastructure, taking advantage of the opportunity to develop a technology and business model that provided a necessary low-cost, high-functionality smart meter to meet its needs when they installed the inaugural grid in 2012. It is now enabling grid operators to increase energy access and improve operations in 22 countries. After developing a prototype, EarthSpark spun off the smart metering company Spark Meter, Inc. [18]. EarthSpark is also developing a scalable model for microgrid development and operation. Bundling technical innovation, community engagement, diverse partnerships and novel financing, EarthSpark is building project-based change and 'de-risking by doing' [17].

> In Les Angles, Haiti, a town that had never before had grid-supplied electricity, EarthSpark developed a new privately-operated, pre-pay microgrid. EarthSpark expanded the grid in 2015 to 430 connections. Over 2,000 people were directly served with 24-hour electricity powered primarily by solar energy and battery storage. Customers' energy costs were reduced by as much as 80% [17].

80 Microgrids by 2022

EarthSpark's goal is to build 80 microgrids in Haiti by the end of 2022. Applying lessons learned from its one grid that is operational, EarthSpark understands that to accomplish this goal, they must address several barriers.

- EarthSpark, working with local partners, led a 100-town microgrid market assessment for Haiti [19].
- They have also worked to clarify the Haitian legal and regulatory landscape for microgrid development and operation.
- The process risk in microgrid development remains high.

Applying Lessons Learned in Haiti

While raising grant money to fund and build the next three grids, the organization is developing plans for the next 40 grids. The actual building of grids, "is by far the best way to de-risk the process for future developments" [17].

WHAT TOOLS, DATA AND LESSONS ARE SHARED WITH DEVELOPERS INTERESTED IN FUNDING A PROJECT?

Private sector actors in the renewable energy arena often rely on data and analysis that are available in the public domain. While private data are usually proprietary, organizations have often provided the critical data that a country and investors need to structure successful renewable energy projects. Below is a sampling of organizations focused on helping countries and their private sector partners access and understand the potential for renewable energy, opportunities for projects, and funding that will make renewable energy projects a reality. Many of these organizations' missions are aligned with the UN's 17 sustainability goals [2]. They work to support countries as they implement their NDCs to reduce CO_2 emissions and limit global warming to 2℃ or less. These organizations offer accessible information, and opportunities to interact with experts from all over the world who can apply best practices to specific projects.

United Nations Climate Change

With 197 Parties, the United Nations Framework Convention on Climate Change (UNFCCC) has international membership and is the parent treaty of the 2015 Paris Climate Change Agreement. UNFCCC is also the parent treaty of the 1997 Kyoto Protocol. The ultimate objective of all agreements under the UNFCCC is to stabilize atmospheric GHG concentrations at a level that will prevent dangerous human interference with the climate system, within a time frame that allows ecosystems to adapt and enables sustainable development [20].

International Renewable Energy Agency (IRENA)

Founded in 2009, IRENA is an intergovernmental organization that supports countries in their transition to a sustainable energy future; 180 countries are actively engaged with IRENA [21]. IRENA provides a wide range of products and services that include [22-31]:

- Annual reviews of renewable energy employment.
- Renewable energy capacity statistics.
- Renewable energy cost studies.
- Renewables readiness assessments, conducted in partnership with governments and regional organizations, to help boost renewable energy development on a country-by-country basis.
- The Global Atlas, which maps resource potential by source and by location.
- Renewable energy benefits studies.
- REmap, a roadmap to increase renewable energy use and meet the 2050 Paris Agreement goals.
- Renewable energy technology briefs.
- Facilitation of regional renewable energy planning;
- Renewable energy project development tools like Project Navigator (an

online platform providing comprehensive, easily accessible, and practical information, tools and guidance to assist in the development of bankable renewable energy projects), the Sustainable Energy Marketplace an investment catalyst, and the IRENA/ADFD Project Facility that funds renewable energy projects.

Sharing lessons learned, IRENA holds workshops such as one in June 2019 during which representatives from countries with enterprising renewable energy goals—those who have pledged 70% to 100% renewable power targets by mid-century. IRENA publishes the findings from such workshops [32].

In August 2019 the IRENA and UN Climate Change (UNFCCC) announced that they are jointly increasing efforts to fight climate change by promoting the widespread adoption and sustainable use of renewable energy [33].

The Low Emission Development Strategies Global Partnership (LEDS GP)

Founded in 2011, LEDS GP enhances coordination, rapid information exchange, and cooperation among countries and international programs. LEDS leaders and practitioners from over 350 institutions and 118 countries collaborate through innovative peer learning, forums, and networks to support the formation and implementation of low emission development strategies. The organization focuses on providing support to developing countries and regions. LEDS GP engages leaders from institutions across government agencies, technical institutes, international agencies and non-governmental organizations (NGOs). It operates regionally in Africa, Asia, Europe and Eurasia, Latin America and the Caribbean and has six technical global working groups plus a global secretariat [34].

United States Agency for International Development's (USAID's) Power Africa

Launched in 2013 by USAID, Power Africa brings together technical and legal experts, private sector participants, and governmental representatives from around the world to work in partnership with the goal of adding more than 30,000 MW of cleaner, more efficient electricity generation capacity and 60 million new home and business connections [35]. The Power Africa Toolbox makes available tools that assist with early stage transaction support, finance, policy development, regulatory reform, capacity building and information resources. [36]

American Cities Climate Challenge and The Renewables Accelerator

Bloomberg Philanthropies' American Cities Climate Challenge, founded in June 2018, is a two-year acceleration program with powerful new resources and access to cutting-edge support to help cities meet or exceed their near-term carbon reduction goals.

The Renewables Accelerator, an initiative of the Climate Challenge, supports U.S. cities in procuring renewable energy as they seek to meet these goals. Jointly led by Rocky Mountain Institute (RMI) and World Resources Institute (WRI) and facilitated by the Urban Sustainability Directors Network (USDN), the Renewables Accelerator offers technical support to 25 selected challenge cities and to over 100 USDN members interested in powering their cities with renewable energy. They facilitate peer exchange among cities and share lessons learned from other large renewable energy buyers. [37]

National Renewable Energy Laboratory (NREL)

NREL is a national laboratory of the U.S. Department of Energy, Office of Energy Efficiency and Renewable Energy. This U.S. government organization advances the science and engineering of energy efficiency, sustainable transportation, and renewable power technologies and provides the knowledge to integrate and optimize energy systems. NREL works with organizations through research partnerships, licensing of NREL technologies, support for cleantech stakeholders, and fostering the clean energy economy. Some of the tools and opportunities to receive support from NREL on renewable energy development include [39-42]:

Data visualization and geospatial tools: NREL's geospatial data science researchers have developed tools that allow users to apply its data. The tools help determine how much electricity can be produced from residential solar systems or what renewable resources are available in a specific area.

*Map*s: NREL offers an array of web-accessible maps to support renewable energy development and electrical generation projects.

Data resources: NREL offers geographic information system (GIS) data resources for a variety of renewable energy technologies. The datasets are designed to be used in GIS software applications.

Case Study—NREL Tools Help Determine the Economic Benefits of Rooftop Solar in Mexico

In 2016 NREL provided technical assistance to the Government of Mexico (GOM) under the USAID Mexico Clean Energy Program. This assistance contributed to the country's planning efforts as it prepared to meet its clean energy targets by deploying rooftop solar technologies [43].

Background

In 2015 the GOM declared its clean energy participation targets—30% by 2021 and 35% by 2024—under its Energy Transition Law and General Climate Change Law. This regulation established the framework for advancing Mexico's clean energy and climate goals, thus advancing its emerging clean distributed generation (DG) market. To foster that growth in an inclusive and equitable way that serves investors, ratepayers, utilities, and society, the GOM needed hard data to answer tough questions [45].

In 2016, the NREL team used its System Advisor Model (SAM) software tool to explore the economics of distributed solar PV in Mexico. SAM is a free, state-of-the-art platform for simulating the performance and economics of renewable energy projects. Among other renewable energy technologies, SAM offers a user-friendly, detailed treatment of distributed photovoltaic (DPV), including rooftop solar systems. The model takes into account customer consumption patterns, retail electricity rates, DPV compensation schemes, system pricing, and a variety of other technical and economic inputs. It is used to create hourly generation profiles for rooftop solar projects, perform return-on-investment analyses, and test the impact of various DPV public policies on customer economics [44].

Replicating the Solarize Campaign Across U.S. Cities

The City of Portland's Climate Action Plan established a goal to reduce carbon emissions 40% by 2030 and 80% by 2050. Recently, its city council established a goal to be 100% renewable in all economic sectors by 2050. The first Solarize campaign started as a community-led movement to help Portlanders overcome the financial and logistical barriers to installing solar power at their properties. Three years of Solarize Portland campaigns resulted in over 600 solar installations and 1.7 MW of new residential solar PV capacity. Solarize has been replicated over 170 times in 18 different U.S. states and abroad [40].

Solar Compensation Policy with the Energy Regulatory Commission

The first analysis conducted with the Energy Regulatory Commission of Mexico (CRE) in July-September of 2016, was designed to inform internal discussions at CRE, focusing on how customers might be impacted by prospective changes to DG metering and billing arrangements in Mexico. Results of the analysis were used to inform, and update Mexico's DG regulatory framework in February 2017 [46].

Potential Benefits of Residential Sector DG and Energy Efficiency

The second analysis was conducted in July 2016 under the leadership of Mexico's Secretariat of Energy, analyzing the potential benefits of residential sector DG and energy efficiency from the perspectives of individual customers, the Mexican Secretariat of Finance and Public Credit, and the environment. The analysis uncovered that there is a disconnect between where the greatest potential benefits exist for the state, versus where it is most financially attractive for customers to invest in DPV systems. Mexico's Secretary of Energy concluded that without a public policy intervention, DPV's "penetration in the market will be very slow, and the environmental and social benefits will not be observed in the short- and medium-term." Well-supported public policy changes can bridge the gaps between benefits for governmental and commercial interests. In January 2017, Mexico Secretary of Energy Joaquin Coldwell released a report summarizing the findings [44].

CAN ENERGY PROFESSIONALS DO MORE?

Organizations that support renewable energy expansion are found in nearly every country in the world. Individual researchers and consortia of organizations across countries, regions and continents are pooling their resources. Their members are conducting research, providing tools and analysis, and promoting transparency through information exchange. The information is shared through print, digitally, via human interaction, or at ministerial meetings. The commitment to sharing information and expertise is ubiquitous. As practitioners, there are a multitude of opportunities to share expertise. The opportunities are as varied as working with a local community group desirous of moving to deploy renewable energy systems, serving on advisory boards, educating elected officials about policy development, or reaching out internationally to help not-for-profit entities. Sharing expertise, best practices

> "It's important to communicate that the situation is tough, but it's also important to pivot to resilience and to ideas of what is possible for us to protect ourselves. Even bigger countries like India have told me, 'Maybe India can't move forward the same way that Costa Rica can, but that doesn't mean that a city in India the size of Costa Rica cannot think big and move faster to clean energy.' That was a very empowering idea… In my country, if you want to get people excited, you have to say that this will make us a country that could inspire others." Monica Araya, Costa Rica Limpia [5].

and lessons learned are the means by which our world will reach the goals of renewable energy application and deployment.

ARE LESSONS LEARNED IN THE DEVELOPING WORLD APPLICABLE TO THE U.S.?

Yes! Leadership and vision are critical; if at present it does not come from the top leaders, it can come from the private sector advocating for and working with the state and local governments. In a recent report to its shareholders, a U.S. energy company relies upon the studies and expertise that national and international groups provide, employing the information in much the same way as developing countries. The U.S. also contributes to best practices. A study done in western Texas is now the basis of an international model that can be modified based on each country's or application's unique circumstances. It supports integrated transmission planning and renewable energy generation development [45]. Co-produced by USAID and NREL, *The REZ Process: A Guidebook for Practitioners* [47], is based on the Texas 2008 initiative, Competitive Renewable Energy Zones (CREZ) Transmission Optimization Study.

As we globally accept the challenge of building a low CO_2e energy supply, the free exchange of shared information helps build the political will to free the flow of funds and deploy new technologies.

CONCLUSIONS

Costa Rica, Uruguay and India provide important examples for other developing and developed countries that seek to rapidly and effectively begin using renewable energy and allay their dependence on fossil fuels. There are similarities in actions that helped each country to rapidly progress in its adoption of renewable energy: 1) leadership with a vision and the will to develop policies that support the adoption and use of renewable energy, 2) a government that is a stable partner to private investment in renewable energy, and 3) commitment to electrify the country's transportation systems.

Are lessons learned and best practices being shared effectively? The lessons and best practices freely communicated in print and digitally, as well as through worldwide conferences, webinars, and workshops, provide evidence that yes, they are being shared effectively. There is a commitment from both governmental and non-governmental organizations to provide tools and resources for accurate information to those making energy policy, including funding commitments, in their respective countries.

Can those in remote villages find out what worked 1,000's of kilometers away? In this era when most of the world relies on mobile phones to access information, there is some irony in the fact that access to electricity dictates when and if one's phone is charged. However, those working in developing countries are increasingly creating their own innovative solutions, new technology, and business models suited to bringing electricity to remote locations throughout the world. These models and technology are developed with the intent to replicate them across the globe.

What tools are available to a developer interested in privately funding a project? Can data and lessons learned be freely shared in the private sector? The private sector can easily access tools and critical data and analysis that assist in the planning, funding and implementation of renewable energy projects. Access to proprietary information can be challenging. However, there are now enough examples of successful renewable energy projects of varied sizes, sources and locations, that private entities wanting to find viable opportunities now have access to accurate and timely information. In addition, the most successful countries are those where the policies clearly support partnerships with the private sector, and those lessons are not being lost on countries that have yet to develop similar ones.

What more can we as energy professionals do to provide needed expertise and best practices to the developing world? The answer is a clear and resounding, "get involved!" There is an urgency and need on every level for expertise, and the opportunities abound to help both locally and internationally. The time is now; jump in and be part of the information exchange.

Are there lessons we can apply to the U.S. from the developing world? Though the U.S. government currently is not taking a leadership role in passing policies to support and promote renewable energy, there is much that the U.S. can and does learn from other countries. States and cities, along with private companies, continue to independently exercise strong commitments to increase the use of renewable energy. Those that lag behind will have the benefit of learning from their neighbors. In the not too distant future, the U.S. will begin again to be a global leader and adopt best practices.

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China-Nigeria Relations in Crude Oil Production and Local Initiatives for Petroleum Refining

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ABSTRACT

This article examines China's engagement with Nigeria in the petroleum production industry and the need for harnessing local initiatives for petroleum refining. Nigeria is a major exporter of crude oil yet must import refined petroleum products to meet domestic needs. Using primarily secondary data sourced from journal articles, books and reports of local and international organizations, this article examines how China-Nigeria relations contribute to meeting the need for refined petroleum in Nigeria and how harnessing local initiatives can improve Nigeria's energy and environmental situation.

INTRODUCTION

China-Nigeria relations manifests in economic, political, social and technological ways. This article examines China's engagement with Nigeria in the area of petroleum production and the need for harnessing local initiatives for petroleum refining. Despite Nigeria's total refining capacity of 445,000 bbl/d (barrels of oil per day) from its conventional refineries, insufficient refining output leads to scarcities of refined products within the country. To handle these shortages, Nigeria has a history of importing refined petroleum products to meet its needs [1]. The importation of refined products contributes to high rates of unemployment, under-utilization of raw crude oil, and high costs for refined petroleum products [1].

With the aid of secondary data sourced from journal articles, books and reports of local and international organizations, this article examines: 1) the nature and dynamics of China-Nigeria relations in the area of petroleum production in Nigeria; 2) China's contributions to meeting the need for refined petroleum in Nigeria; 3) the local initiatives for refining petroleum that exist in Nigeria; and 4) how China's economic engagement within Nigeria might contribute to harnessing local initiatives for petroleum refining. Prior to examining these dynamic issues, perspectives on China-Nigeria relations and an overview of petroleum production in Nigeria are discussed.

Perspectives on China-Nigeria Relations

Diplomatic relations between Nigeria and China were established in the 1970s. This developed despite the hostilities associated with Chinese support for Biafra during the Nigerian civil war of 1967-1970. A Nigerian delegation visited Beijing in 1972 and concluded an open-ended agreement on trade and technical cooperation [2]. During the regime of General Sani Abacha (1993-1998) when Western aid was suspended because of the regime's human rights violations, Nigeria adopted a *look east* policy which strengthened the Beijing-Abuja alliance and helped built trust between the nations. Since 1999 when the democratic government was reinstated in Nigeria, all Nigerian presidents have visited China to strengthen economic ties. For example, President Goodluck Jonathan's visit to Beijing in 2013 led to a $3 billion (U.S.) loan for infrastructure which included funds to expand the airports in Lagos, Kano, Abuja and Port Harcourt. Following President Buhari's visit in 2016, Nigeria was offered an infrastructural loan of $6 billion [3]. In addition to providing assistance to Nigeria for infrastructural development, China has also provided military support to the Nigerian government to tackle insecurity problems [4,5]. In 2006, President Hu Jintao of China visited Nigeria and addressed joint sessions of the Nigeria's National Assembly after which both nations signed a memorandum of understanding (MOU) establishing a strategic partnership [2].

Past literature that considers economic relations between China and Africa including Nigeria offers both positive and negative perspectives on China's motives. The positive perspective argues for win-win economic interactions between China and Africa. Scholars who view China's relations with Africa from a positive perspective do so because of China's contributions to infrastructural development in Africa. In the view of Brautigam and Gaye "Chinese teams have built bridges, hydroelectric power plants, ports, highways and even railroads" [6]. Western donors turned away from infrastructure development but the Chinese listened to what Africans wanted. The sale of resources to China should be seen in a positive developmental light as its "demand for Africa's commodities is creating new opportunities for African governments to realize the hopes of their people for a better life. Countries that set their house in order… can position themselves to benefit, and those that do not will find their resources continue to be simply a curse—with or without China" [6]. The negative perspective views the China-Africa relationship as a new form of imperialism. It considers China's motives in Africa as a form of resource exploitation [7-9]. Literature critical of Chinese-Africa relations is growing because of the nature of their trade relations. Some argue that the relationship has mostly benefited Chinese interests since its primary focus on extractive industries overlooks how local regimes undermine governance through violations of human and democratic rights [3,6,10].

An intermediate perspective encourages African countries to cautiously embrace opportunities offered by China without neglecting the promotion and preservation of its interest. As Mlambo et al. postulated, China-Africa relations showed that the relationship presents both opportunities and challenges for African countries [11]. Africa needs to be cautious when entering into economic and political ties with China. While Africa should embrace the opportunities offered by the relationship with the Chinese, it should also preserve and promote African interests [3]. Within the context of petroleum production, there is need for Nigeria to cautiously embrace the investment opportunities offered by China while not neglecting indigenous approaches to petroleum refining.

CHINA'S INVOVEMENT IN NIGERIA'S PETROLEUM INDUSTRY

The early development of the petroleum industry in Nigeria can be traced to 1908, when the German Bitumen Corporation, started petroleum exploration activities in the Araromi region of western Nigeria. These pioneering efforts were affected by the outbreak of World War I in 1914. After the war, oil exploration resumed in 1937, when Shell D'Arcy (the forerunner of Shell Petroleum Development Company of Nigeria) was awarded sole concessionary rights for the territory of Nigeria. After years of investment and investigation, commercial quantities of crude oil were discovered at Oloibiri in the Niger Delta in 1956.

Production of crude oil in commercial quantities and exports from the Nigeria's Oloibiri field began in 1958. Initially crude oil production yielded 5,100 bbl/d. This occurred prior to the country's independence in 1960. Afterwards oil production has been characterized by agitations from host communities and human rights violations by the government. Scholars have documented and analyzed the confrontations that have characterized oil production which involved the host communities, multinational corporations and the government. For example, Obi studied how oil extraction and the dispossession of the people of the Niger Delta resulted in incidents of violence—clashes between rival armed groups, militias and government troops—which included killings, sabotage of oil pipelines and installations, and a thriving transnational trade in stolen oil (or illegal oil bunkering) [12]. Frynas also examined the consequences of foreign oil production activities in rural communities of the Niger Delta [13]. The study offered a comprehensive overview of the environmental and social impacts of oil operations. Ako and Okonmah asserted that oil production made the Niger Delta a place characterized by violent conflicts that threatened local and international economic stability and security [14].

Petroleum production is Nigeria's most important form of international trade. It contributes over 90% of the foreign exchange earnings of Nigeria and about 80% of capital and recurring expenditures [15]. The Nigerian oil industry has predominantly served the interests of both domestic and international elites. This usually results in the export of crude oil and shortages of refined petroleum products in Nigeria. Despite having four petroleum refineries, Nigeria exports crude oil and imports refined petroleum products for domestic consumption. Nigeria expends large sums on fuel subsidies, money that could otherwise be used for education, health, agriculture, rural development, transport, land and housing. Given Nigeria's consumption of about 45 million liters of motor fuel daily, the existing refineries produce only 12 million liters daily [16]. The situation is more challenging in riverine areas of the Niger Delta. This has contributed to the innovation of a locally contextualized strategies for petroleum refining, called artisanal refineries [17].

China-Nigeria Relations in Petroleum Production

China' economic engagement with Nigeria in petroleum production is associated with China's governmental decisions to more fully utilize its resources abroad. After twenty years of rapid development, Chinese oil companies have become important players in the international oil and gas markets of Africa [18]. The origin of China's involvement in oil production in Nigeria can be traced to the 1990 when Nigeria's former military head of state, Sani Abacha, invited Chinese state-owned companies into the country. He died in 1998.

When Chief Olusegun Obasanjo became Nigeria's president in 1999 interactions between Nigeria and China began to increase. Obasanjo's administration strengthened Nigeria's ties with China with its *oil for infrastructure* policy, a central element of Obasanjo's economic strategy towards China. His government auctioned oil drilling rights that required Chinese and other Asian preferred bidders to commit to providing Nigeria with major infrastructure projects [19]. This new scheme was motivated by the Nigerian government's disillusionment with the paltry impacts on national infrastructure after 50 years of cooperation with western countries, impatience with conditional aid, and by Obasanjo's personal impressions of the infrastructure he saw while visiting China [20]. Following persistent lobbying by the Nigerian government, Beijing opted to engage with Obasanjo's plan, believing it created opportunities to both increase China's presence in Nigeria's oil sector and secure lucrative new construction contracts for Chinese companies. Obasanjo persuaded Chinese companies into Nigeria by offering them the right of first refusal (RFR) on oil blocs at discounted rates or with signature bonus waivers in return for their commitments to invest in infrastructure projects. The first bidding round held under these rules occurred in 2005, with 77 blocs on offer. Most Western companies abstained due to the RFR and requirements that bidders acquire local partners. Only 44 of the blocs were awarded; of these, nearly half were withdrawn because the winners defaulted on payments. Chinese companies failed to bid, mistakenly believing that they had previously secured the blocs during negotiations with the Nigerian government. The following year China's president, Hu Jintao, visited Nigeria and signed a MOU that committed Chinese companies to participate in the rehabilitation of Nigeria's decayed rail network in the expectation of receiving oil blocs in future bidding rounds. Chinese companies were given responsibility for the 1,315-km Lagos–Kano section, the plan being to install a double-track, standard gauge railway line.

Bilateral trade between Nigeria and China grew from $384 million (U.S.) 1998 to $3 billion in 2006. Most was attributed to the oil sector. In 2005, Nigeria agreed to supply Petro China with 30,000 bbl/d (4,800 m^3/d) of oil. During China's President Hu Jintao's visit in 2006, four oil drilling licenses were secured with the agreement that China would invest $4 billion in oil and infrastructure development projects. Since then, both nations have negotiated a plan to improve bilateral relations. The key component of the agreement was to expand trade and investments in agriculture, telecommunications, energy and infrastructure development. Furthermore, China agreed to purchase a controlling stake in the Kaduna oil refinery targeted to produce 110,000 bbl/d (17,000 m^3/d). Nigeria also gave preference to Chinese oil firms for contracts for oil exploration in the Niger Delta and Lake Chad Basin. In 2006, China also agreed to grant a loan of $1 billion to Nigeria to help upgrade and modernize its railway networks. That same year the China Offshore Oil Corporation (CNOOC) purchased shares worth $2.3 billion in an oil exploration block owned by a former Nigerian defense minister. China also pledged to invest $267 million to build the Lekki Free Trade Zone near Lagos. The effect of these investments in Nigeria, however, reveals an uneven balance of investment as there is no corresponding investment in China by Nigeria [2,20,21].

Another aspect of China's economic engagement in the oil and gas industry is the award of pipeline contracts. The Nigerian National Petroleum Corporation (NNPC) in 2018 was awarded two natural gas pipeline contracts worth $2.8 billion. The first was awarded to Oando and OilServe for 200 km of the 614 km Ajaokuta-Kaduna-Kano pipeline to connect the eastern, western and northern parts of the country. The China Petroleum Pipeline Bureau and Brentex were awarded the second contract for another 200 km of pipeline between the Kaduna and Kano Terminal Gas Stations. These contracts were aimed at boosting gas production and supply [22].

NIGERIA'S PETROLEUM REFINING CAPACITY

Petroleum refining in Nigeria started about a decade after oil was discovered in the Niger Delta area in the 1950s. In 1965 the refining capacity of Nigeria was 38,000 bbl/d and it has grown over the years. Because of the challenges associated with the optimal performance of existing conventional refineries, Nigeria imports over 80% of its refined products. This creates huge potential for local refining. Nigeria consumes over 17 billion litres of premium motor spirit (PMS) annually and over 90% is imported. Imported PMS is primarily sourced from Europe and the U.S. Additionally, Nigeria consumes over 400 million litres of aviation fuel annually, most of which is sourced from the U.S. [23].

Imports account for 100% of the aviation fuel supplied to Nigeria due to the inability of existing refineries to produce the fuel, most also from the U.S. With oil prices expected to remain low in the medium to long terms, the focus on increasing domestic refining capacity should become imperative. Lower oil prices mean cheaper crude feedstocks and higher refining margins for refiners. Separately, following the combination of rising shale oil production in the U.S., continued oversupply in the export market and weak demand, future markets for Nigerian crude are uncertain [23].

The importation of refined petroleum products adversely effects on the Nigeria's economy. Table 1 shows Nigeria's continued heavy reliance on imported fuel. This reflects low refinery capacity in Nigeria, which provided only 17% of its domestic needs in 2017[25]. Table 1 also shows that Nigeria generated large positive balances from 2005 to 2014 which contributed to healthy reserves as high as $53 billion in 2008 and above $45 billion in 2014 [26]. During the period crude petroleum averaged more than three times the 2000 level but fell to less than half the 2014 price from 2015-17; this led to a rapid deterioration in the trade balance [24].

These data indicate that massive importation of refined petroleum products

Table 1. Nigeria-World Fuel Imports 1995-2017 and Trade Balance (in million U.S. dollars).

Year	*Fuel Imports*	*Nigeria's Total Imports*	*Trade Balance*
1995	425	8,222	4,120
2000	462	8,721	12,254
2005	839	20,754	25,035
2006	2,436	26,523	32,692
2007	3,071	32,357	33,849
2008	6,252	49,951	31,870
2009	3,522	33,906	22,836
2010	4,999	44,235	44,333
2011	7,763	56,000	69,641
2012	6,516	51,000	63,700
2013	9,865	56,000	46,400
2014	9,326	60,000	42,879
2015	5,320	45,658	6,556
2016	7,493	35,194	-2,311
2017	9,232	45,000	-2,534

Source: UNCTAD [24]

has negative consequences for Nigeria's economy especially when crude oil prices are low. This makes it necessary for Nigeria's refining capacity to be improved.

The inability of existing refineries to meet Nigeria's needs for refined petroleum has necessitated the establishment of modular refineries. China is among those countries helping Nigeria to achieve this goal. Modular refineries are processing plants that are constructed on skid-mounted structures. Modular refineries were used in the 1940s and again in the 1970s when portable crude topping units for the production of straight-run gasoline, diesel oil, and heavy fuel were developed [27]. Each structure contains a portion of the entire process plant. Using interstitial piping the components are linked to form a manageable processing facility. They are manufactured in controlled conditions, fully assembled and tested prior to overseas shipment, and can be quickly installed at a site. Constructing a modular refinery in Nigeria requires a design capacity not exceeding 30,000 bbl/d; plants with capacities above 30,000 bbl/d must be upgraded to a full conventional refinery. One of the advantages of modular refineries is that they can be situated near crude oil sources which reduces the cost of moving the oil from a source of production to remote refineries. In 2019, the Edo State government of Nigeria signed an MOU with a Chinese firm, Peiyang Chemical Equipment Co. Limited (PCC), to build a modular refinery. Although the interest of China in establishing modular refineries in Nigeria is laudable, there are more local benefits when modular or artisanal petroleum refining are harnessed.

Local Initiatives for Petroleum Refining

Local initiatives for petroleum refining in the Niger Delta of Nigeria are associated with operators of artisanal refineries. Artisanal refining refers to small-scale or subsistent distillation of crude petroleum over a specific range of heating points, to produce useable products such as kerosene, fuel, diesel, bitumen and waste products. It involves mostly traditional skills with little reliance on advanced technology. Artisanal refineries use a simplified version of fractional distillation (locally called cooking). They cook barrels of crude oil with firewood and other mixtures in a sealed tank constructed with metal. The crude then evaporates and passes through two parallel pipes joined to the tank through a cooling water bath. Refined products drip slowly into containers at the end of the processes, with different products emerging at different intervals.

Product yields depend on the refinery methods used and the specific properties of the crude oil available. Most Nigerian crude oil grades are heavily diesel-rich. The quality of products obtained vary widely. To address this, artisanal refineries sometimes purify diesel by mixing it with kerosene to reach large refinery standards. Artisanal refineries rely on illegal bunkering for the supply of crude petroleum [28]. A typical refinery might produce 10,000 bbl/d. Since the plants are not automated, they are less capital intensive but require more labor. These plants are simply designed, efficient and inexpensive to configure. The low initial investment cost allows indigenous private investors to enter the refining business [29].

The origin of the technology for artisanal refining of crude oil in the Niger Delta region is indefinite. One perspective is that the Biafra side of the Nigeria civil war (1967 to 1970) invented the technology for small scale refineries when its refined petroleum needs could not be met because of a blockade by federal forces. After the war, this refining technology evolved into the present generation of artisanal refineries used in Nigeria's Niger Delta oil-producing region. A second claim links the technology to illicit relationships between oil workers and idle young men in the Niger Delta who earned their living on illicit profits. Proponents of this theory believe that unknown engineers offered the technology to the locals to provide them with a means of livelihood following the collapse of farming and fishing vocations in the wake of oil-induced environmental devastation. Another theory claims that the practice was started by makers of a local alcoholic beverage (gin), made by distilling palm wine. This distillation technology was successfully used locally to refine petrol, diesel and kerosene [31]. The ingenuity of the palm-wine tapper apparently sparked the demand for needed refined petroleum products when supplies from legitimate sources were limited. Yet another account suggests that Niger Delta militants started artisanal refining because they were in need of refined petroleum products for their boats after their supplies were cut off by the government during the Niger Delta militancy. This situation was then compounded by poverty and lack of access to petroleum products in the challenging terrain of the Niger Delta [17].

Despite the uncertainties associated with identifying the origin of artisanal refineries, the consensus opinion is that it evolved from the technology originally used for the refining of a local dry gin called *ogogoro* which was later adapted to refine crude oil. The adaptation became widespread because of the inability of the people to earn an adequate income from agricultural activities and the production of gin. This was due to the destruction of farm land, aquatic life and raffia palm used to produce *ogogoro* and was caused by oil pollution. It is believed that most people engaged in the artisanal refining of crude oil in the Niger Delta did not set out originally to refine crude oil. They started by bursting pipelines to siphon petrol and diesel for sale. It was a dangerous activity. People were being arrested by security agents or incinerated if accidents occurred when siphoning. Artisanal refining was a safer alternative and the process was more widely adopted. Eventually the military became interested in how militants in the mangrove forests were obtaining fuel for their boats and generators. It was discovered that refined products were being supplied by artisanal refiners. This marked the beginnings of the destruction of artisanal refineries in the Niger Delta by the military [17].

These theories of the origins and nature of Nigeria's artisanal refineries notwithstanding, more salience is placed on the notion of existential exigency and the pressure placed on artisanal refiners to earn a living any way possible. Artisanal refineries respond to the perennial scarcity of petrol, diesel and kerosene in Nigeria which are used for fueling vehicles, providing electricity to homes and business and for domestic cooking [31]. The necessity for these products is understandable against the background of inadequate electricity supplies. In parts of the Niger Delta where consumer petroleum products cannot be readily obtained, products from illegal refineries are indispensable. Established marketers of petroleum products also patronize artisanal refined pans which they mix with products from other sources in the underground reservoirs of filling (gasoline) stations dispensing them to unsuspecting customers. Products from artisanal refineries are also used by industrialists and businesses that depend on electric generating plants in the absence of a reliable electricity supply. With the end of insurgency and the commencement of an amnesty program, artisanal refining became an income source for demobilized insurgents and idle youths. Local refining of petroleum using this innovative strategy ultimately provided employment opportunities for the teeming youths in rural areas of the Niger Delta.

Failure to harness local initiatives for petroleum refining encourages insecurity and environmental pollution in the Niger Delta because government security agents discover and destroy artisanal refineries often harming the environment in the process. Currently, the federal government of Nigeria uses armed forces known as the Joint Task Force (JTF) to fight against oil theft and the proliferation of artisanal refineries. This is an ineffective long-term strategy. The JTF activities temporarily interrupt some of the refining operations, most camp owners and workers do not consider JTF's activities as a major threat to the sustainability of their business. This is because artisanal refineries can quickly be rebuilt in new locations.

China's Experience in Local Refining Initiatives

China can contribute meaningfully to harnessing local initiatives for petroleum refining in Nigeria because of its past success in supporting independent refineries despite the challenges involved. These refineries started with low-level technology and improved over time. Nearly 70% of the capacity of China's independent refiners is concentrated in the eastern province of Shandong, where China's second largest oil field, Shengli, is located. Shandong's independent refineries developed along with Shengli in the 1960s. The central government permitted local governments to collect oil that leaked from Shengli's pipelines and to build refineries as a means of easing local resistance to the development of Shengli, which involved local governments giving up land, an important source of tax revenue. Shengli is geographically larger than China's other oil fields. This fact supported the growth of independent refineries in Shandong since it was difficult for the Ministry of Petroleum (and later the NOCs) to tightly control Shengli's production, some of which regularly flowed to the independent refineries. Other dispersed independent refineries were often located near other oil fields or port facilities.

China's experience indicates that encouraging innovation and local initiatives for petroleum refining yields positive results. Empirical research and surveys of business activities support the idea that innovation leads to new and improved products and services, higher productivity and lower prices.

China and India funded innovative solutions which helped to turn them into economic super powers. They developed their own technologies through indigenous factories which started crudely initially but improved over time. Today, China not only meets most of its indigenous technological needs, but also exports technologies and the resulting industrial products. China's independent refiners now account for about one third of China's total refining capacity. From 2005 to 2015, the output from independent refiners increased from 832,000 bbl/d to 4,175,000 bbl/d. Their share of China's total refining capacity jumped from 13% to 29% [32].

INTERNATIONAL REASEARCH AND DEVELOPMENT

Economies that have consistently high levels of innovation also tend to have high levels of growth [33]. The experiences of several economically advanced countries indicate that research and development (R&D) is crucial for harnessing homegrown innovation to support sustainable development. The U.S. has a history of providing support for R&D both at home and internationally. For example, the former U.S. President, Barack Obama asserted in February 2014 that:

> "We need to build a future in which our factories and workers are busy manufacturing the high-tech products that will define the century… Doing that starts with continuing investment in the basic science and engineering research and technology development from which new products, new businesses, and even new industries are formed."

The postulation above emphasizes investment in technology and future capabilities which is transformed into new products, processes and services. The economic growth of any nation depends on the capacity to educate, innovate, and build long-term national investments in basic and applied R&D. Mutually reinforcing and complementary investments in R&D by both the private and public sectors work in concert to support the development, production, and commercialization of new products and processes. The benefits associated with promoting innovative activities are captured in the following statement of President George W. Bush in 2004:

> "America leads the world because of our system of private enterprise and a system that encourages innovation. And it's important that we keep it that way. See, I think the proper role for government is… to create an environment in which the entrepreneurial spirit flourishes… the government can be a vital part of providing the research that will allow for America to stay on the leading edge of technology… I think we ought to encourage private sector companies to do the same, invest in research."

Since innovation has long been recognized as an important driver of economic growth and development, it is pertinent that the Nigerian government collaborate with China to research existing local technologies for refining petroleum. Lessons can be learned from the experiences of countries such as the U.S. by promoting innovation through R&D. National investment in R&D includes investments by the central governments, states, colleges and universities, businesses and non-profit organizations.

Some recent studies prove that the artisanal refinery operators have initiated efforts toward R&D. They have discovered that pollution from their refining activities can be minimized by using gas cookers for heating the crude oil during the refining process instead of using wood and waste crude which produces a thick smoke [17].

Lessons for Nigeria

The various tertiary institutions in Nigeria that specialize in petroleum-related activities are crucial to supporting collaboration with universities in China. These institutions include: the Federal University of Petroleum Resources (FUPRE) in Effurun in Warri in Delta State, the Petroleum Training Institute (PTI) in Effurun in Delta State, and the Department of Petroleum Engineering, University of Benin in Edo State.

Such collaboration is necessary because it is possible to enhance local technologies for petroleum refining. This leads to improvement in quantity and quality of refined products. The major challenge associated with R&D in the artisanal refining of petroleum is inadequate funding for research in Nigeria's educational institutions. This makes it difficult for researchers to collaborate with the local refiners to improve existing technologies. It is important for governmental and non-governmental organizations both within and outside Nigeria to assist researchers who are interested in discovering ways of improving local technologies for petroleum refining. Developed countries have demonstrated that funding innovative projects helps solve problems that countries face. For example, American research universities have been a model of innovation throughout the world, addressing complex economic, social, scientific and technological problems [34]. Universities contribute to the quality of the economic infrastructure in a state or region by developing knowledge-linking activities that enhance the commercialization of new technologies, support organizational and community change, and assure the education of workers and professionals [35].

Improving Nigeria's indigenous technologies for petroleum refining through R&D could yield breakthroughs that reduce the pollution that they create. If the quality of these refineries is enhanced, Nigeria's government can license entrepreneurs enabling them to engage in legal production activities.

The legalization of artisanal refineries will make it possible for entrepreneurs to purchase crude oil at a rate stipulated by the government. This will help to check the problem of crude oil theft by the refiners. Some of the benefits that Nigeria can gain from scaling up the production by artisanal refiners include diversifying the economy as a result of linkages with manufacturers, creating a more employment and providing a reliable supply of petroleum products, and reducing poverty and inequality.

Refineries are also required in Nigeria for strategic reasons. They will help increase the county's gross domestic product and earn more revenue for government. The byproducts of petroleum refining are useful for plastics manufacturing and agricultural purposes. The use of chemical pesticides and fertilizers can increase agricultural productivity. Since the Nigerian government is presently advocating increased participation of Nigerians in agricultural activities, harnessing the homegrown solution for petroleum refining has a complementary role in increasing agricultural productivity. Farm machinery also requires petroleum.

CONCLUSIONS

Although some may argue that since oil production by artisanal refineries is low, increasing output may not substantially impact in Nigeria's economy. This is not true. An analysis of Chinese national oil companies (NOCs) in Africa and Central Asia suggests that Chinese NOCs have developed technologies that can create profitable oil projects in Africa at sites once considered by western oil companies to lack value [17,36]. Regardless, China' efforts to engage economically with Nigeria in petroleum production are associated with China's governmental decisions to utilize its resources abroad. While African countries should embrace the opportunities offered by their relationships with the Chinese, it is imperative that African interests be preserved and promoted [3].

Legalizing and scaling up the activities of artisanal refiners will improve the economy and security of the Niger Delta region. This is because easily influenced unemployed youths engage in militant activities and oil pipeline destruction which causes the federal government to depend mainly imported refined products. For example, the frequent crises in the Niger Delta region from 2002 to 2006 paralyzed the oil sector, making Nigeria dependent on imported petroleum products. As the past managing director of the Nigerian National Petroleum Corporation, Mr. Funso Kupolokun asserted, Nigeria imported 100% of its needed petroleum products when all four of the nation's refineries in Warri, Kaduna and Port Harcourt closed because militants destroyed the main feeder pipeline [37].

For local petroleum refining initiatives to be effectively harnessed, the collective efforts of the Nigerian state and research institutions in Nigeria is required. The present approach of the federal government in destroying artisanal refineries should be reconsidered. This is because it prevents the articulation of the ingenuity of the operators of artisanal refineries which can be improved through R&D. It is important to review extant laws on petroleum refining. Such laws prohibit the use of indigenous technology in the Niger Delta since it is not recognized as credible for licensing. For example, section 3(1) of the Petroleum Act states that no refinery shall be constructed or operated in Nigeria without a license. The government through a well-articulated policy framework should formalize the activities of the indigenous refineries by licensing their operations in Nigeria [17].

Instead of signing MOUs with foreign countries to establish modular refineries the Nigerian government should focus on harnessing successful local technologies for petroleum processing. This strategic engagement could end petroleum theft and the environmental pollution caused by security forces when artisanal refineries in Niger Delta are destroyed. By legalizing the operation of indigenous refineries, the availability of petroleum products in Nigeria will increase.

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Commercial Implementation of Low Pressure, Low GWP Refrigeration System

Andrew Smith and Ben Kungl

ABSTRACT

Hydrofluorocarbon (HFC) and hydrochlorofluorocarbon (HCFC) based refrigerants are being phased out globally by government regulatory bodies due to known issues with their ozone depletion potentials (ODP) and global warming potentials (GWP). A new refrigerant fluid class, hydrofluoro olefins (HFOs), has shown promise as a potential class of low GWP and zero ODP fluid.

Owners and operators of refrigeration systems which utilize HFC/HCFC refrigerants are faced with the need to replace the refrigerants being utilized in their systems due to new regulations. There are opportunities to transition systems to advanced design and control platforms that allow for substantial energy and maintenance cost savings. However, many owners and operators of refrigeration systems are slow to adopt these new refrigerants.

This article reports on the energy reduction and technical benefits from a commercial implementation of an advanced controls and design architecture from Oxford Energy Solutions, Inc. that utilizes the low-pressure refrigerant HFO R-513a, a low GWP, and zero ODP refrigeration fluid. Specifically, this article reviews the total system input electricity consumption before and after the installation of an HFO R-513a system using Oxford's architecture and implementation at a site in Ontario, Canada. The analysis provides a pre-project versus post-project reduction of over 80% in the total input electricity required which results in substantial cost savings.

INTRODUCTION

Beginning in January 2015, the United States Environmental Protection Agency (EPA) issued the final requirements for a 100% phase-out of R-22 refrigerants in the U.S. The plan issued by the EPA requires a linear year over year reduction of R-22 that can be manufactured or imported to the U.S. with the result that by year end of 2019 no new or imported R-22 will be allowed into the country [1]. Accelerated phase-out regulatory programs for HFC based refrigerants are underway in Europe as a result of the F-Gas Regulation, in Canada due to Environment and Climate Change Canada (ECCC) and elsewhere. This has driven the need for refrigerants using chemical compounds with lower GWPs, improved efficiencies, and wider operating envelopes that are safe working refrigerants (e.g., meeting the ASHRAE A1 classification). As a result of research and development by the refrigeration industry for replacements to HFC refrigerants that exhibit low ODP and GWP, hydrofluoro olefins (HFOs) have emerged as commercially viable candidates. The refrigerant discussed in this article, Opteon™ XP10 by Chemours, HFO-513a, is a refrigerant developed to be a replacement for R-134a in new systems and for retrofitting in existing systems. HFO-513a is a blend of 56 wt% HFO-1234yf and 44 wt% HFC-134a. It has a GWP value of 573 as determined by the IPCC's Fifth Assessment Report (AR5) [2]. The Oxford Energy Solutions platform architecture has been developed to take advantage of this low-pressure refrigerant. Utilizing modern advances in controls and equipment, it offers a wide operating range.

BASE CASE SYSTEM

The customer, Vanessa Meats, is a butcher and deli operation located in Vanessa, Ontario. The owners required modifications to the refrigeration system at the site to accommodate business expansion, and begin the phase-out of R22 refrigerants.

Table 1. Properties of R-513A refrigerant [3].

ASHRAE Number	*R-513A*
Composition	HFO-1234yf/R-134a
Weight %	56.0/44.0
Molecular weight g/mole	108.4
Boiling point at 1 atm (101.3 kPa) °C	-29.2
Critical pressure kPa [abs]	3,766
Critical temperature °C	96.5*
Liquid density at 21.1 °C (70 °F) kg/m^3	1,185.7
Ozone depletion potential (CFC-11 = 1.0)	0
AR5 global warming potential	573
ASHRAE safety classification	A1
Temperature glide °R	0

*Note: The high critical temperature is advantageous when operating in warmer climates.

The base case before project implementation included 18 separate refrigeration units with a total of 50.5 kW input power capacity. The project entailed replacing units 5 through 8 (see Table 2), for 14 of the 18 individual units. They represented 30.2 kW of installed load and 60% of total system capacity.

ENERGY EFFICIENCT SYSTEM

The design architecture presented here is based on fundamental refrigeration system design principals which include: 1) lowering the required system head pressure; 2) lowering the required compressor ratio which reduces the required internal heat of compression in the system; and, 3) maintaining the lowest possible system pressure differentials to achieve a long-term platform that targets zero refrigerant leakage.

These features are partially achieved with Copeland's Scroll compressors and the Emerson EXV platform [4] which enables the system to utilize a low pressure HFO refrigerant (HFO-513a) and operate at a very low compression ratio. The system operates at an average low-pressure range of 4 psig and an average medium pressure range of 20 psig. The discharge pressure is 85 psig in the summer and 60 psig in the winter. Multiple low temperature loads are controlled from a single low temperature compressor which operates at different speeds based on load requirements. As a result, the freezers and low-temperature cases operate at extremely low compression ratios. This reduces secondary heat influences such as the heat of compression and motor heat on the low temperature loads by as much as 80%.

One of the platform's key design features is the removal of non-essential valves. Removing the liquid, hot gas defrost and/or suction line solenoid valves, evaporator pressure regulators and mechanical head pressure control valves eliminates the pressure drops and inefficiencies that result from these devices. Additional advantages include potential leak reduction through the elimination of gasketed surface valve connections/fittings and reduced maintenance costs.

Superheating the refrigerant vapor prior to the compressor is a standard requirement in refrigeration systems that ensures there is no liquid entering the compressor to cause mechanical damage. Traditionally, suction vapor superheating is achieved using a portion of the evaporator system itself; however, this reduces refrigeration system efficiency by reducing the amount of latent heat work performed in the evaporator(s). Using this methodology, evaporator superheat is minimized through control of the evaporator expansion valves. Instead, it is superheated by using the built-in heat exchanger in the suction accumulator.

Table 2. Base case system configuration.

#	*Refrigerant type*	*Saturated suction temperature (°F)*	*Saturated condensing temperature (°F)*	*End use*	*Qty.*	*kW*	*kW total*
1	404	-10	120	Freezer	1	4.4	4.4
2	404	-10	120	Freezer	1	4.4	4.4
3	22	28	120	Cooler	1	6.0	6.0
4	22	28	120	Cooler	1	5.5	5.5
5	22	45	120	A/C	1	5.8	5.8
6	134	20	120	Gravity deli meats	2	1.4	2.8
7	407c	25	120	Production/sausage rooms	1	5.6	5.6
8	290	-10	120	Glass door upright freezers	10	1.6	16.1
							50.5

Table 3. Retrofit equipment summary.

	Replacement equipment identification	*Calculated heat load (BTUH)*	*Saturated suction temperatures (°F)*	*Defrost heaters FLA, 230 VAC (amps)*	*Room / case temp (◦C)*
1	Brema B- 5 door freezer	5,500 LT*	-7	16.5	-18
2	Brema 2 door MT	1,200	29	N/A	3
3	Boston 8ft MT	9,000	20	N/A	
4	Chicago 8ft (Section 1) Gravity MT West	4,000	20	N/A	3
5	Chicago 8ft (Section 2) gravity MT east	4,000	20	N/A	3
6	RTE cooler	8,800	29	6.25	3
7	Fresh cooler	12,200	29	8	3
8	Cut room	14,000	35	N/A	8
9	Sausage process room	21,000	25	16	3
10	Rear process	22,000	35	N/A	8
11	Blast cooler	12,000 **	25	8	3
12	Fermenting/play	12,000 **	25	8	3

*Note: adds 9,000 (BTUH) to MT load.
**Note: Dependant on load.

The suction accumulator heat exchanger (refer to B in Figure 1) extracts heat from the liquid refrigerant providing liquid sub-cooling benefits, while simultaneously providing the required vapor superheating. This provides free liquid subcooling from the architecture of the system thus improving refrigeration system efficiency. The liquid subcooling generated in the system averages 15°F to 30°F without expending additional energy to achieve subcooling (i.e., supplemental cooling units).

With the reduced super heat in the evaporators, there is an economic and system benefit for the installation of an additional piping loop through the condenser to further increase system subcooling – and capacity (refer to A in Figure 1). The average subcooling gain with this architecture results in liquid temperatures around 55°F with a saturated condenser temperature of 85°F. Typically, 30°F of subcooling results in a 16% gain in system capacity which is established at no extra input costs. The liquid sub-cooling guarantees a high energy liquid at the inlet of every expansion device without the negative effects of flash gas in the liquid line that occur when the refrigerant approaches saturation.

The total sub-cooling gain in the system is achieved by reducing the amount of superheat in the evaporators. The additional condenser sub-cooling loop and heat exchanger in the accumulator all contribute to maximizing the system subcooling and capacity.

Utilizing a lower pressure refrigerant has many additional benefits. Foremost there is less mechanical stress on key system components such as piping, fittings, gaskets and connections. This substantially lowers the risk of potential refrigerant leaks. The reduced system refrigeration charge due to the design architecture improves system safety and simplifies training requirements.

The use of electric defrost allows for a simpler system architecture and helps maintain a lower condensing pressure. This means less piping and fewer valves are needed. Also, a common liquid and suction header can be used throughout the facility. Electric defrost eliminates the need for hot gas defrost reducing the valves required at the rack and thus eliminating a major cause of conventional refrigeration system leakage.

ANALYSIS AND RESULTS

The measurement and verification (M&V) process followed the requirements of the International Performance Measurement and Verification Protocol (IPMVP). It entailed measurement of the total site incoming input power utilizing a root mean square (RMS) power logging electrical meter before and after project implementation. The meter utilized for both pre- and post-project measurements was a Candura EnergyPro. The incoming electrical supply consisted of a single-phase, three-wire 240V supply (see Figure 5). Current and voltage on all three lines were monitored at five second intervals for 35 days starting 21 February 2019 prior to the new refrigeration equipment installation and for 10 days after project completion beginning 13 September 2019.

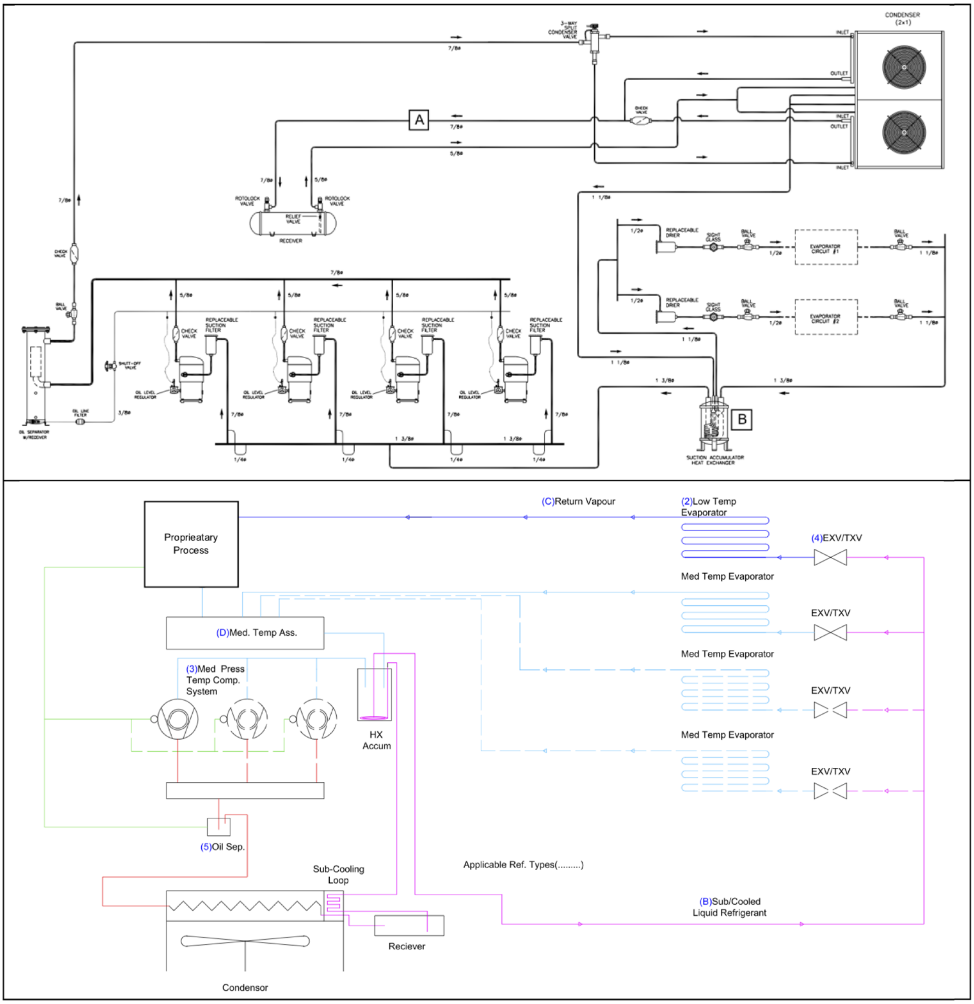

Figure 1. Typical system architecture layout schematics.

The power data taken during the pre- and post-project data periods were utilized along with historical climate information (from climate data website for the Brantford Airport in southwestern Ontario) to determine the annualized energy consumption for pre- and post-project periods. Using the data in Figure 3, the hourly average power values can be determined which indicate that the facility has daily operational cycles. To differentiate between the daily operational cycles, it was necessary to derive temperature to power correlations for three separate cases of data both pre- and post-project periods:

1 – Mondays through Saturdays, 9:00 am through 4:00 pm.
2 – Mondays through Saturdays, 5:00 pm through 8:00 am.
3 – Sundays all day.

These temperature-to-power correlations were used to determine the 2018 annualized electrical consumption for historical hourly average temperatures. The preliminary base case data was then linearly adjusted to account for the increase in refrigeration footprint from a pre-project value of approximately 27.9 m^2 (300 ft^2), plus gravity cases and freezers (see Table 2, #6-8), to a post-project value of 131.0 m^2 (1,400 ft^2), plus cases and freezer (see Table 3). Tables 4 and 5 summarize the analysis of savings before and after project implementation.

The post-project data was measured during a relatively warm week in September 2019, when the average outdoor ambient temperature (OAT) was 18.5°C, relative to the pre-project data that was measured in late February/ early March 2019 when the OAT was -3.1°C.

For example, during the post-project data collection period on 17 September 2019, the average hourly rate of electricity consumption (18.9 kW) at an average temperature of 11.4°C was almost 20% lower than the pre-project average hourly rate of electricity consumption (23.1 kW) on 28 March 28 2019 at 6.3°C (a much lower temperature). This 20% reduction in energy is measurable before accounting for an increase in refrigerated space.

CONCLUSIONS

This article details the reduced energy use and technical benefits from the commercial implementation of an advanced controls and design architecture that utilizes a low-pressure refrigerant with a low global warming potential. The methodology and operating characteristics of the system architecture described led to the lower compression ratio capabilities of the compressors, and boosts the low temperature system into medium temperature architecture. With proper control strategies and refrigerant control measures, the new system is able to take advantage of some key benefits of using a low-pressure refrigerant (R-513a), and the untapped abilities of the scroll compressors that operate so efficiently at this low-pressure differential.

The pre-project versus post-project M&V analysis validated a reduction of over 80% of the total required input electricity which resulted in cost savings. This reduction is after relevant baseline adjustments have been applied for the increase in refrigerated area. Each specific installation will have unique characteristics that will drive the final energy savings.

Table 4. Energy and cost savings summary.

Base case			
	kW	*kWh*	*Cost ($)*
Preliminary	25.4	222,305	33,346
Adjusted	119.3	1,044,834	156,725

Energy efficient case			*Project savings*		
kW	*kWh*	*Cost ($)*	*kW*	*kWh*	*Cost ($)*
18.8	165,093	24,764	100.4	879,741	131,961

Table 5.

Normalized cost savings (electricity costs estimated using $.15/kWh).

	Pre-project	*Post-project*
Cost/m^2	$ 1,196	$ 189
Cost/day	$ 429	$ 68
Cost/hour	$ 17.89	$ 2.83

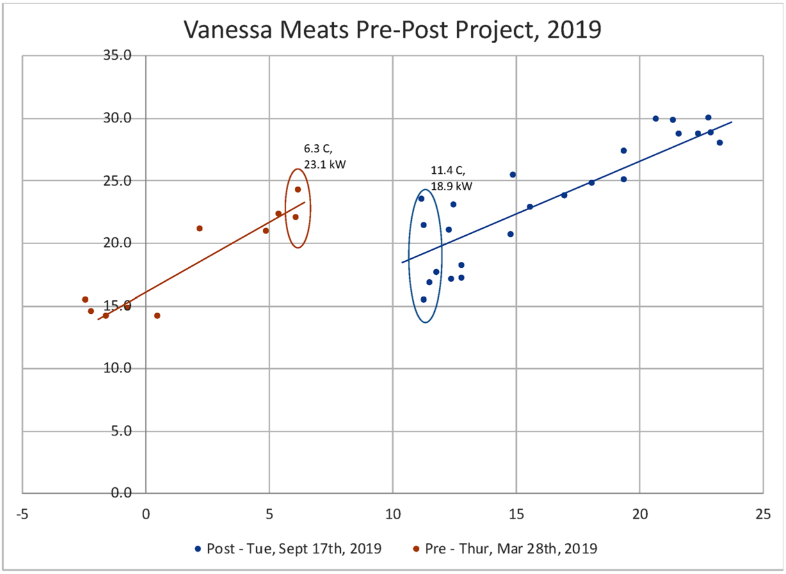

Figure 2.

Single day pre- and post-project temperature and power comparison.

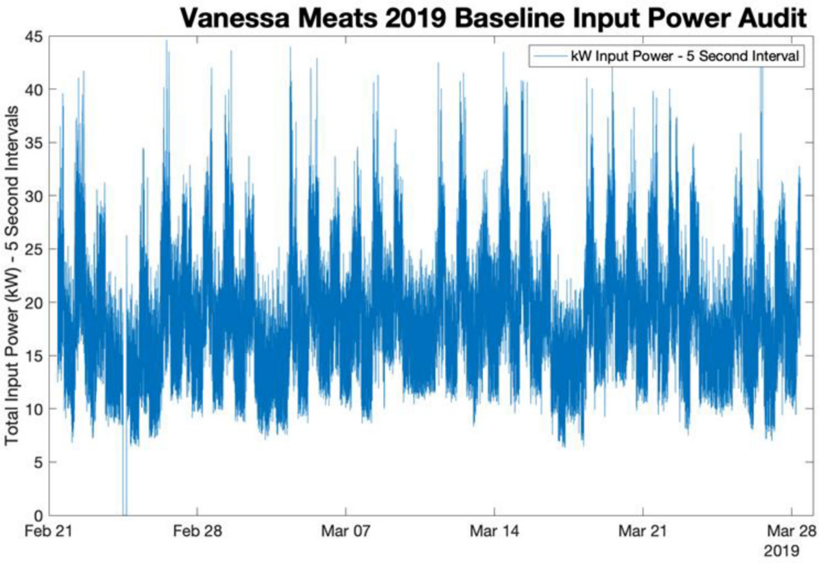

Figure 3. Pre-project 5 second total input power.

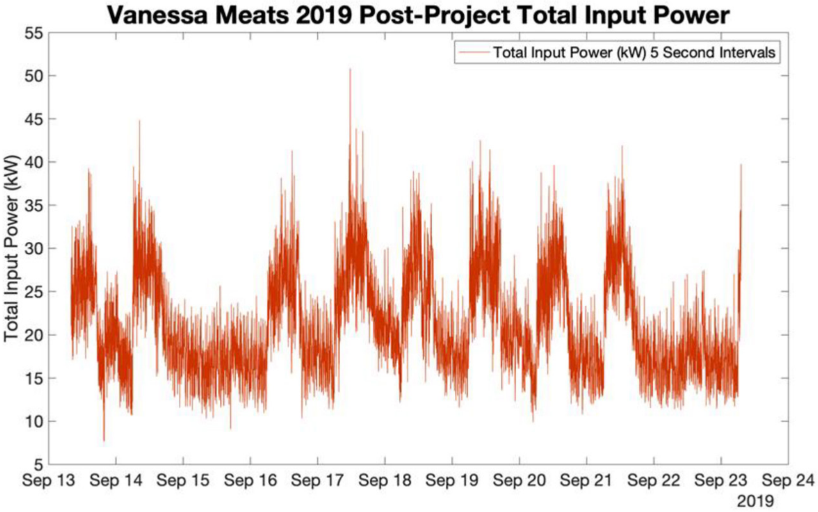

Figure 4. Post-project, 5-second total input power (kW).

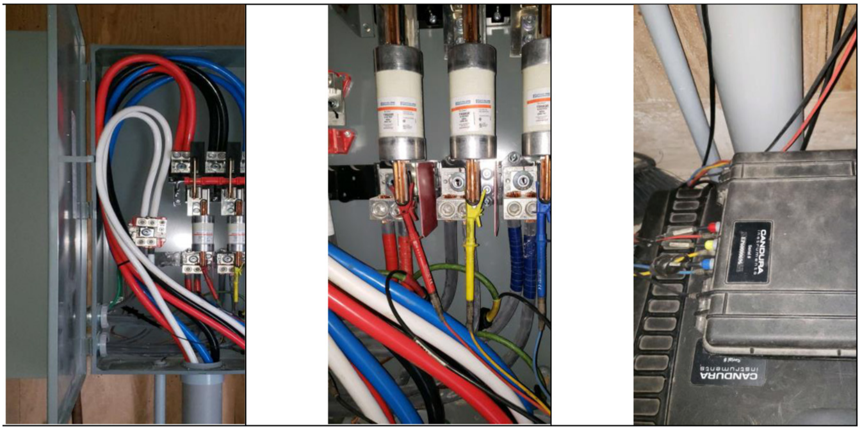

Figure 5. Power meter installation (Vanessa Meats).

Figure 6. Pre-project installation.

The fundamental system design approach is to maintain the lowest technically feasible operating refrigerant pressure differentials at all times through advanced controls and sensor technologies while minimizing internal heat generation. The overall system architecture does not rely on one main component to improve system efficiency. The Oxford Energy platform relies on the combined net effects of all the individual benefits of these system components working together to achieve improved system efficiency with a new HFO-blended, low-pressure refrigerant. Combined with a low pressure drop system and compound refrigeration architecture to enable a zero-leak rate, this approach provides a system that sets a new standard in reliability, low maintenance and energy efficiency.

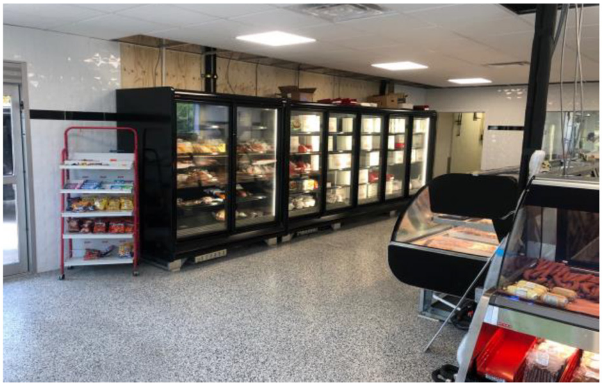

Figure 7. Post-project Arneg refrigeration case.

Figure 8. Post-project Arneg refrigeration case installation.

This platform also allows refrigerant piping architectures that operate at much lower overall system charge to meet or exceed impending refrigerant regulations across North America. Due to the lower operating pressures, the medium and low temperature architectures can be exempt from existing governing body regulations for field certified pressure tests and submissions such as those required by the Technical Standards and Safety Authority (TSSA) in Ontario.

Future areas of study could include the investigation of other low-pressure, lower GWP refrigerants and the application of this approach to refrigeration system design in to larger installations. The potential to study the utilization of different piping materials (e.g., a crimped/compressed fitting systems) and configurations is also appropriate.

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* * *

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