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Sustainable microgrids: Economic, environmental and social costs and benefits of microgrid deployment

Yael Parag *, Malcolm Ainspan

School of Sustainability, The Interdisciplinary Center (IDC) Herzliya, 8 University St., P.O.Box 167, Herzliya, 4610101, Israel

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ABSTRACT

This paper addresses the costs and benefits associated with microgrid development relative to the costs and benefits of conventional generation interconnected to a bulk transmission and distribution grid. The costs and benefits are classified as: environmental (avoided environmental damage costs); economic (mainly employment multiplier effects); deferral or avoidance of transmission and distribution investment costs; and greater access to electricity supply that is highly reliable and resilient. Deficiencies due to the lack of relevant available data and of research on economic modeling of microgrids at the societal level are discussed. The context in which these costs and benefits are measured is the Israeli electricity market, which features a highly centralized, vertically integrated electricity company (Israel Electric Corporation, IEC) with some legacy distribution companies. Moreover, because Israel's transmission and distribution infrastructure investment have declined significantly over the past several years, the Israeli market provides a useful basis for analyses of microgrids as an alternative to such large-scale investments.

The analysis reveals that under reasonable assumptions reflecting the current state of microgrid technologies, microgrids may constitute a viable, cost-effective alternative to additional central- station generation requiring new investments in transmission and distribution infrastructure. Specifically, using reasonable assumptions regarding 10-MW incremental investments in a microgrid and in central-station generation with necessary transmission and distribution investments, the analysis indicates that, when considering the reliability, T&D investment deferral, local economic, environmental, and social costs and benefits of each alternative, the net benefits to the Israeli economy from selecting the incremental 10-MW investment in a representative Israeli microgrid may exceed $13,000,000 per year. However, when local economic benefits are not considered, the net benefits decline to approximately $260,000 per year. For perspective, generation capacity additions by the Israel Electric Corporation have averaged 166 MW from 2008 through 2018, reaching 13,775 MW of installed capacity by the end of 2018. Total annual capital investment has averaged approximately $1 billion since 2015, about $400 million of which has been in the generation sector. The paper concludes with future research directions, with an emphasis on integrating engineering analysis, scenario simulation, flexibility, and quantifying social/equity (“fairness”) effects of microgrids.

Introduction

Over the past several years, microgrid development has been a significant topic for energy policy development (Hirsch, Parag, & Guerrero, 2018). While a large share of this development has taken place in developing countries with limited access to reliable energy supply, there is some progress being made in microgrid development in the OECD countries, particularly in North America (Sioshansi, 2018). This development depends in large part on a combination of technical, economic, and regulatory factors. In these OECD countries, regulators have attempted to prioritize microgrid development by using their existing sets of cost-benefit analytical tools. Such tools have been used to determine the prudency of utility investments (e.g., California Public Utilities Commission, 2018), but may be inadequate for evaluating microgrid projects at specific locations throughout such a utility's transmission and distribution systems. Consequently, in many OECD countries, policy tools have reinforced an existing bias toward larger centralized infrastructure rather than distributed systems, including microgrids (Levin & Thomas, 2016; Sioshansi, 2018). This paper attempts to provide a framework for assessing benefits and costs of microgrid integration, based on the current state of microgrid development. Notably, some of the benefits, such as improved resiliency, have not been defined well, making quantification difficult. In such cases, we rely on definitions rooted in system planning, and use the techniques from engineering economics, in addition to regulatory practice

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* Corresponding author.
E-mail addresses: yparag@idc.ac.il (Y. Parag), ainspanm@netvision.net.il (M. Ainspan).

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to date, to develop our economic analysis. In addition, this paper attempts to provide an approach to evaluating microgrids that synthesizes the techno-economic methods commonly employed in power systems engineering with the broader policy approaches commonly found in the trade literature on distributed energy resources, particularly microgrids (e.g., Microgrid Knowledge[1]).

In this paper we use the definition of a microgrid that was developed for the U.S. Department of Energy by the Microgrid Exchange Group, an ad hoc group of research and deployment experts: a microgrid is "a group of interconnected loads and distributed energy resources within clearly defined electrical boundaries that acts as a single controllable entity with respect to the grid, and that can connect and disconnect from the grid to enable it to operate in both grid-connected or island (Ton & Smith, 2012).

System-wide benefits

The paper analyzes various system-wide technical, environmental, economic and social benefits potentially associated with microgrids deployment, as detailed below:

Techno-economic benefits

One potential benefit is the reduction/avoidance of transmission and distribution costs associated with the displacement or deferral of large, centralized generation and bulk transmission/distribution systems by microgrids with distributed resources closer to load centers. In addition to the reduction in direct investment costs, microgrids also offer "option value" by allowing its component infrastructure to vary modularly with changes in loads, lead times, and/or renewables targets. Option value is based on the concept of "real options", which is an approach to valuing alternative investment projects based on the option to continue, adapt, or abandon an investment in the future, in light of future information becoming available.[2] The ability to adapt investments as uncertainty regarding these factors is resolved, largely removes the risks – and avoids the costs - inherent in conventional grid investments (Ruotolo, 2018).

Additional benefits are the flexibility in integrating targeted levels of renewable and demand-side technologies to meet future electricity uses that have yet to be defined, in addition to future electricity demand growth. Specifically, microgrid-enabled flexible Demand Response, by supplanting slow or inefficient generation, reduces both the costs associated with operating generating plants at part-load and frequent cycling of these units. Demand Response, by providing operating reserves more flexibly than these units, thereby facilitates increased penetration of renewable energy more efficiently and at lower cost (Pinson & Madsen, 2014; Stadler et al., 2016). The value of this microgrid-enabled DR flexibility depends significantly upon the impacts of such renewable targets on fossil units' retirement, many of which provide significant system flexibility.

Environmental benefits

A primary motivator in developing microgrid policy is its ability to integrate renewables at an economic scale not easily achieved under a centralized electricity system alone. For example, microgrids can often use storage and demand-side resources to mitigate the risks of frequency and voltage fluctuations associated with intermittent renewables, at levels of locational granularity that is not easily accommodated by centralized generation and transmission and distribution (T&D).

There is significant variation among energy and environmental regulators in quantifying environmental benefits of non-fossil generation. In this paper, quantifying environmental benefits focuses primarily on a common set of environmental damages and associated valuations used by regulatory authorities in the US and Europe; this set will include CO_2, SO_x, NO_x, and particulates. Although not quantified in this paper, there are also benefits associated with the reduced costs of integrating intermittent renewables, primarily wind and solar energy. These costs include: the additional costs of voltage support and frequency regulation, and ramping caused by the intermittency of wind and solar resources.

Economic benefits

Several countries and local authorities investigating the benefits of developing microgrids are considering the benefits to the local or regional economy, primarily the growth in primary and secondary employment opportunities and regional product. Examples of direct investment associated with microgrid development include energy efficiency, grid upgrades, and extension of microgrid technologies to research and development of other "smart" technologies.

Social benefits

The paper assesses social benefits in terms of improved access to generally accepted reliability and quality levels relative to current levels, and the value of such improvements. To date, the literature has focused on qualitative assessments and on determining the benefits that can be attributed directly to microgrid development (e.g., Campbell, Ryan, Rozite, Lees, & Heffner, 2014; Haramati et al., 2018). The metrics used for quantifying social benefits will be discussed in greater detail in this paper, and are intended as a starting point for such quantification.

Resiliency

The electricity economy has yet to develop a consistent definition of resiliency across developed electric systems. One accepted definition, offered by the National Infrastructure Advisory Council, is "…the ability to reduce the magnitude and/or duration of disruptive events. The effectiveness of a resilient infrastructure or enterprise depends upon its ability to anticipate, absorb, adapt to, and/or rapidly recover from a potentially disruptive event." (U.S. Department of Homeland Security, 2009). Consequently, quantifying resiliency benefits from microgrid development – and from distributed energy in general – in a consistent manner has proved elusive. This paper uses the results of resiliency valuations from the electricity economic- engineering literature to develop an initial estimate of the value of resiliency at a systemwide level, despite microgrids' greatest value of operability in island mode being at a local level. Nevertheless, estimation of resiliency value at more granular levels is an area for further research.

The associated costs of microgrid development are difficult to determine due to: (1) scale economies present in microgrid sizing (which are not generally present for microgrid benefits); (2) the components of the microgrid itself; and (3) declines in the costs of renewable, storage and demand-response technologies included in most microgrid configurations. This paper looks at microgrids of various sizes and configurations in order to develop a range of microgrid costs.

The paper continues as follows: The next section provides an overview of the relevant existing concepts in the literature and presents the characteristics of the Israeli electricity markets, on which the model is applied. The following section summarizes the methodology and data sources and presents and discusses the results. The closing section concludes and proposes directions for further research.

The benefits and costs of microgrids

In this section we draw on sources from academic and consulting studies addressing each benefit discussed above.

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[1] https://microgridknowledge.com/white-papers/microgrid-policy/.

[2] Conventional investment finance models implicitly assign a zero option value to all investment alternatives. For additional detail, see Trigeorgis, L., 1996. Real options: Managerial flexibility and strategy in resource allocation. MIT press. *Investment under Uncertainty*.

Avoidance/deferral ("flexibility") of transmission and distribution ("T&D") investments

Recent literature on microgrid economics has adopted the evaluation tools used to evaluate distributed generation and demand-side resources in rate cases and integrated resource plans. Examples of such literature include work by the Lawrence Berkeley National Laboratories (Brown, Jiuping, Xiaorning, & Koutlev, 2001), Energy and Environmental Economics (2011), Synapse Energy Economics (2018), Mendota Group (2014), Morris (2012) and Mishra and Palanisamy (2018). This literature indicates a wide range of the costs of avoiding or deferring transmission and distribution costs, with most estimates either in the ranges of $60–80 thousand per MW or above $100 thousand per MW. Some literature explicitly uses "real options" valuation by Farzan (2013), Martzoukos and Teplitz-Sembitzky (1992) to quantify the deferral value and modularity associated with modular alternatives to T&D investments, albeit without addressing microgrids. Option value was not considered in this paper, mainly because the complexity of modeling the properties of stochastic inputs (e.g., fuel prices and infrastructure costs) in a small, changing market like Israel, would greatly expand this paper beyond its intended scope.

Environmental benefits

Environmental benefits are generally measured in terms of the avoided emissions costs associated with fossil-based generation, primarily SOx, NOx, and particulates ("PM-10"). There are various approaches to calculating those avoided costs, focusing on the extent to which emissions markets internalize all associated avoided costs, primarily based on epidemiological studies supporting a correlation between air quality problems and increased mortality/morbidity, as indicated in (Fowlie, 2010) and Linn and McCormack (2017). Studies addressing these benefits in a manner similar to that of this paper include: Lee (2010), NYSERDA (2014), Xiaoling (2015). The environmental benefits focus primarily on the avoided social costs of carbon, generally estimated between $20 and $50 per ton. Studies addressing microgrids as facilitators of renewables integration include ABB (2015), Industrial Economics Inc. (2015), and Morris, Bogart, Dorchak, and Meiners (2009). These articles largely address the cost reductions that microgrids offer to the overall electric system, mainly those associated with solar and wind output intermittency.

Economic benefits

There are a variety of accepted approaches to estimating the macro-economic benefits associated with alternative energy technologies. While most of the literature focuses on renewable and smart-grid technologies at the utility level, there is growing interest in estimating the benefits of microgrids integrating both technologies at smaller scales. There is also a substantive body of literature refuting such analyses – which tend to indicate significant macro-economic benefits, mainly because of the "business-as-usual" (i.e., existing system configuration without significant microgrid investment) counterfactual assumed in these analyses. Examples of analyses estimating such macro-economic benefits include: World Energy Forum (2012), Stoddard, Abiecunas, and O'Connell (2006) and English, Menard, Jensen, Hellwinckel, and Ugarte (2011). It should be noted, however, that none of these studies examined the economic impact of microgrids, focusing instead on investments in potential components of microgrids, such as solar photovoltaic facilities.

It should be noted that there is a body of literature casting doubt on the assumptions employed and on the usefulness of performing such analyses (e.g., Morris et al., 2009). Morris et al. (2009) paper, in particular, cast doubt on the "counterfactual" assumptions in the "pro-economic benefits" research, identifying several deficiencies in the existing literature on employment multipliers, including: (1) the absence of clear criteria for defining employment and domestic product as "incremental"; (2) the lack of clear accounting of the associated job losses and benefits of trade with regions that have a comparative advantage in the technology (e.g. microgrid development and operations), thus overestimating any net benefits from microgrid installation; (3) the use of basic input-output analyses that do not account for economies of scale, thereby inadequately reflecting the difference in multiplier effects between small, targeted projects and broad implementation; and (4) the focus on economic benefits from increased producer surplus, without considering potential counterbalancing changes to consumer surplus. By ignoring consumer surplus, economic multiplier studies tend to overestimate the overall welfare benefits to society.

Resiliency

Quantifying the effects of resiliency requires a clear definition of resiliency itself. Proposed definitions and initial attempt at quantification has been proposed by Sandia National Laboratories (Staid, 2017), the US Department of Energy (Executive Office of the President, 2013), and the National Infrastructure Advisory Council (2009) ("NIAC"). Most definitions of resiliency follow the general outline of NIAC and Sandia National Laboratories as "the ability to reduce the magnitude and/or duration of disruptive events", focusing on grid operations and planning for the context of low-probability, high-consequence events such as natural disasters having large-scale consequences to the power grid and surrounding community (Vugrin, Castillo, & Silva-Monroy, 2017). These studies by NIAC and Sandia create scenarios for weather forecast model uncertainty and the probability of system failures, model decision-making by system operators to re-dispatch the bulk electric system in light of those events, and then quantify the loss-of-load impact in light of these scenarios and system operator decisions. While it is possible to translate this loss-of-load impact into an economic value by using a Value-of-Lost-Load ("VOLL") measure, such an approach is likely to underestimate the value of resiliency (Anderson et al., 2018). VOLL is a reliability measure based on conventional probability distributions; resiliency focuses exclusively on the extreme values of those distributions.

However, in the absence of accepted, widely applicable methods for measuring resiliency, we exclude resiliency benefits from our analyses, while recognizing such measurement as critical for evaluating future investments in electricity system infrastructure, including microgrids.

Israel electricity sector

We apply our analysis to the Israeli electricity sector. There are several characteristics of the Israeli electricity sector that likely make it more conducive to microgrid development, and thus provide an appropriate reference point for analyzing the benefits and costs of microgrid development for several reasons. These include:

1. The existence of "legacy" non-utility distribution companies, which have functioned for decades as quasi-microgrids, effectively operating as electricity distribution network companies.[3]
2. The lack of state-vs.-federal jurisdictional issues affecting the nature of microgrid participation in other electricity markets, particularly the US market. The significant investment in clearly differentiating wholesale markets on bulk transmission systems under federal jurisdiction from retail markets on the local transmission and distribution systems under state jurisdiction is driven in part by growth in distributed energy resources in

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[3] https://pua.gov.il/decisions/documents/1454.pdf (Hebrew).

general, and microgrid projects in particular. In contrast, Israel, with economic regulation of the electricity sector taking place only at the federal level, provides an opportunity to direct resources toward microgrid development, rather than resolution of state-federal jurisdictional issues.

3. Israel faces projected electricity demand increases of 2.5%–3.0% per year (Israel Public Utilities Authority, 2017), which is significantly higher than that of other OECD countries(U.S. Energy Information Administration, 2016). Rapid load growth increases the risk that existing and planned transmission infrastructure will be unable to satisfy that growth reliably, primarily due to the large, multi-year investments required. In contrast, microgrids can be developed modularly, to satisfy load growth as it occurs (e.g., Kumar et al., 2018).
4. Israel's transmission and distribution infrastructure investment have declined significantly over the past several years, primarily due to the tenuous financial condition of the Israel Electric Corporation associated with the uncertainties surrounding the reforms of Israel's electricity sector. This decline has not only affected electricity supply reliability, but has also made achieving national targets for renewable electricity generation difficult to achieve, since there is insufficient grid investment necessary to reliably deliver electricity from solar facilities in the south to the rest of the country.

In light of the current conditions of Israel's electricity sector and its dominant electricity company, microgrids can present more of an opportunity than a threat to the incumbent Israel Electric Corporation in ensuring compliance with its electricity reliability and security standards.

Methodology and data sources

The objective of this paper is to develop an approach to assessing benefits and costs of microgrid integration, based on the current state of microgrid development, as well as an application of this approach to microgrids in Israel. The total benefits included within this framework are: Environmental benefits from renewables integration; Deferred/avoided transmission and distribution infrastructure investments; Economic growth opportunity; and Social benefits, including access to improved system security and reliability.

While modeling and quantification of the first two benefits have been established in a variety of contexts, including utility-specific system planning, energy policymakers, and economic consultancies, quantification of the latter two benefits has not attained the same level of acceptance. This paper quantifies the environmental and deferred T&D investments following accepted approaches described in the literature review above. However, quantifying economic growth opportunities will be based on results of several studies conducted for renewables and smart-grid integration, with greater weight assigned to studies producing lower multipliers, in the interests of conservatism. Moreover, social benefits will be discussed in more qualitative terms, mainly because valuing equitable access to reliable, secure electricity has not yet been sufficiently addressed.

Data sources and assumptions

Much of the analysis in this paper is based on data from Europe and North America, adjusted to reflect Israeli economic and environmental conditions. It is our hope that reliable Israeli data will become available as Israel gains more experience with microgrid development.

Below is a discussion of the data used and assumptions supporting or complementing this data:

Table 1
Environmental costs for each pollutant.

Pollutant	$US per ton	US cents/g
Particulates	9500	0.95
NO_X	2400	0.24
SO_X	3190	0.319
CO_2	7	0.0007

Environmental benefits

The primary source of environmental data is the Government of Israel. The Israel Public Utilities Authority – Electricity ("PUA") and the Ministries of Energy and Environmental Defense use data provided by the European organization ExternE that assesses the external cost of energy[4]; however, this data has not been updated since, 2010, when the PUA last updated its rate design policy for the generation sector (Israel Public Utilities Authority, 2010). This ExternE data consists of information from Greece, and internalize the external costs of emissions, including damage to the general environment and to public health. The Government has chosen to use data from Greece for several reasons: (1) Similar standard of living as reflected in metrics such as Gross Domestic Product at that time; (2) Similar climates; and (3) Similar demographics in terms of congestion and age distribution. ExternE contains a database of the external costs of various pollutants, including SO_x, NO_x, CO_2, and particulates. ExternE provides estimates for a variety of environmental damages, including damages to health, loss of biodiversity, damage to agricultural production, and damage to raw materials for manufacturing. The quantification approaches used by ExternE include estimates of the average life expectancy, and associated lifetime medical costs.

Tables 1 and 2 below summarize the ExternE environmental costs for each pollutant (Table 1) and their reflection in the premia in electricity tariffs set by the Israeli PUA (Table 2):

The PUA calculates environmental premia for renewables providers based on the environmental costs avoided by substituting renewable resources in a constrained optimal economic dispatch for the existing fossil-based resources in each Time-of-Use rate period (Israel Public Utilities Authority – Electricity, 2010). The table below indicates the premia for each period is reflected in electricity tariffs as follows (in Israeli agorot (1/100 New Shekel) per kWh):

In this paper, these premia are used to calculate the additional avoided environmental costs associated with the renewable generation integrated into a microgrid that would not be integrated in a centralized grid within the same timeframe (e.g., due to a microgrid's greater flexibility in incorporating changes in its resource mix). It is worth noting that the reason for the offpeak premium is that offpeak energy is disproportionately generated by coal, which is the highest polluting fuel in Israel's electricity generation portfolio. The premia are likely to change in the future, as natural gas's share of electricity generation increases, and daily electricity consumption patterns become less "peaky" due to factors such as demand-response technologies and energy storage – both encouraged by microgrid initiatives.

Economic benefits

The data sources used to estimate economic benefits mostly reflect the net benefits from the additional employment opportunities generated to construct and maintain the microgrid. These opportunities will increase domestic product and will likely increase opportunities for skilled workers to relocate to the microgrid area, thereby increasing demand for goods and services

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[4] See http://www.externe.info/externe_d7/.

Table 2
Environmental premia included in Israel's electricity tariffs.

Time-of-day	Premium
Offpeak	9.692
Shoulder	6.110
Peak	8.162

It should be noted that the premia will change with changes to the time-of-use rate structure, the mix of electricity generators assumed for each time-of-day block, and with changes in the environmental costs calculated by the Ministry of Environmental Defense.

Table 3
Annualized levelized cost of electricity for supply technologies included in microgrids.

Annualized levelized cost calculations ($/MWh)	Literature	Values used in this paper
PV	76–150	117.59
Wind	30–60	65.94
Microturbine – natural gas	59–89	83.20
Demand response/energy efficiency	0–50	16
Battery	346–386	350

The assumptions for levelized costs are assumed in this paper for PV, wind and microturbine are based on Lazard (2017), IRENA (2018), Bloomberg Energy Finance (2018); demand response based on Hoffman et al. (2018); batteries based on Lai and McCulloch (2016).

from existing and new businesses. Such economic benefits may be classified as "direct" and "indirect". There is significant variation among multiplier estimates for such benefits, but particularly for indirect benefits. In this paper, we use the most conservative estimates for economic multipliers, published by the World Energy Forum (World Energy Forum, 2012), for both microgrids and central-station combined-cycle natural gas generation, to estimate the increase in employment associated with the microgrid. The added value, in terms of Gross Domestic Product ("GDP") associated with the microgrid, is calculated based on the current Israeli per- capita GDP provided by the Central Bureau of Statistics multiplied by the average salary premium for jobs (both direct and indirect) associated with the renewable energy sector. The average salary premium, expressed as the ratio of the microgrid salary to the average salary, is based on data provided by the National Renewable Energy Laboratory ("NREL") based on US data (Schwer & Riddel, 2004); it is assumed that this ratio is applicable to Israel as well.[5] We then account for the reduction in unemployment compensation per Israeli law resulting from the increased employment opportunities. (The assumptions used for this analysis are included in Table 5).

Reliability benefits

Reliability benefits are defined narrowly in this paper in terms of the Value of Lost Load ("VOLL"), defined as the estimated amount that electricity consumers receiving firm service (i.e., not operating under contracts under which the electric utility can interrupt service) would be willing to pay to avoid a disruption in their electricity service. In this paper, the VOLL is based on estimates provided by the Israel Ministry of Energy, and assumes a customer mix of 50% residential, 40% commercial/small industrial and 10% large industrial (served entirely at transmission voltage). The VOLL values for residential, commercial/small industrial, and large industrial customers are $13, 559, $44,350, and $25,424 (Ministry of Energy, 2011), respectively (assuming an exchange rate of 3.54 New Israeli Shekel per US dollar). The weighted average VOLL across these customer classes is $27,062/MWh. This VOLL is multiplied by the number of annual MWh provided through the microgrid in order to obtain the value of additional reliability.

We note that the assumption that the microgrid will effectively eliminate centralized-grid outage risk may overstate the reliability benefit, and that a better measure would be the "delta" between the reliability of the grid and the microgrid. However, such measures are highly system-specific – and location-specific within each system – and require system modeling that is beyond the scope of this paper.

Nevertheless, while reliability benefits may be overstated, resiliency benefits are not quantified at all, and are likely understated. These "resiliency benefits" are mainly the microgrid's ability to maintain system reliability and security during extreme events affecting the centralized grid, especially to low-income residential customers with little to no ability to mitigate extreme-event risks. We do not quantify these benefits because there is no widely accepted method for doing so (US Department of Energy, 2017). Moreover, due to the lack of accepted measurement methodologies, we do not quantify any social equity benefits associated with microgrids' ability (and likely incentives) to assign higher priority to non-industrial customers in mitigating outage risks and their impacts to these customers. Therefore, our estimates of overall reliability benefits are likely to understate their true value.

Avoided/deferred transmission and distribution investments

A commonly cited example of benefits offered by a microgrid is the ability of the incumbent electric utility (or transmission/distribution Company) to use microgrids to defer T&D investments. The value of these T&D system investment deferral varies widely. For example, this deferral value would be several times greater in urban areas requiring undergrounding of T&D infrastructure than in rural areas allowing above-ground infrastructure across existing utility rights-of-way. In this paper, we assume avoided annual T&D infrastructure costs of $152,393 per MW in our base case, relying on survey data from North America (Synapse Energy Economics (2018) and Energy Storage Association (2018)). Therefore, deferred/avoided T&D costs for the 10-MW microgrid amount to $1,523,393 per year.

Microgrid costs

In calculating microgrid costs, it is necessary to define the characteristics of the microgrid itself. These characteristics include installed capacity, composition of that capacity (grid, storage, micro-generation, and demand response) and the costs associated with building, operating, and maintaining the microgrid. For our purposes, we assume a 10-MW microgrid comprised of 4 MW solar; 1 MW CHP; 3 MW gas micro-turbine; and 2 MW demand response/energy efficiency.

The most commonly used metric for comparing the costs of producing, storing, and curtailing energy is the levelized cost of electricity ("LCOE"). LCOE annualizes the set of capital, other fixed, and variable costs associated with each technology, and

Table 4
Annualized levelized cost calculations: microgrid controller and other development costs.

Annualized levelized cost calculations: $/MWh	
Additional development costs	17.30
Controller costs	7.42

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[5] With regard to microgrid-induced employment additions, it is likely, although not definite, that the resource mix of a microgrid will differ from that of IEC's existing system, thereby requiring employees with a different skill set. Moreover, microgrid investment is more likely to be driven by customer preferences, rather than the capital-raising capabilities and protracted regulatory issues that often delay or impede bulk system investments in Israel. However, to the extent that these issues become less significant (e.g., due to changes within IEC and/or the Energy Ministry and the Electricity Authority), the additional microgrid-linked employment is likely to drop.

divides them by the total projected energy generated over the life of the asset. In this way, LCOE allows direct cost comparisons between fossil-based and renewable technologies.

The formula for LCOE is:

$$LCOE = \frac{\sum_{i=0}^{N} \frac{I_i + O_i + F_i - ITC_i - PTC_i}{(1+r)^i}}{\sum_{i=0}^{N} \frac{E_i}{(1+r)^i}} \begin{cases} I_i & \mathit{Investment\ costs\ in\ year\ i} \\ 0_i & \mathit{O\ \ M\ costs\ in\ year\ i} \\ F_i & \mathit{Fuel\ costs\ in\ year\ i} \\ ITC_i & \mathit{Investment\ tax\ credits\ in\ year\ i} \\ PTC_i & \mathit{Production\ tax\ credits\ in\ year\ i} \\ E_i & \mathit{Energy\ generated\ in\ year\ i} \\ r & \mathit{wacc} \\ N & \mathit{Lif\ e\ time\ of\ project}\ (\mathit{years}) \end{cases}$$

Tables 3 summarizes the levelized costs for each component, based on recent surveys of levelized cost of electricity ("LCOE") for each technology (Lazard, 2014, 2017, 2017a) and the value used in this paper.

In addition, microgrids require investments in controllers and other development costs (Siemens, 2016). Table 4 below indicates the assumed levelized costs of these investments over a 30-year period:

The economic multipliers used to estimate the increase in employment associated with the microgrid presented in Table 5.

Model and key sensitivities

The model is a conventional cost-benefit model, similar to models created for the solar energy sector in Israel (Mor, Seroussi, & Ainspan, 2005) and the Electric Power Research Institute (EPRI US, 2010; Gellings, 2011). These models use a standard set of worksheets providing detail on base-case assumptions and sensitivities on reasonable ranges around those assumptions.

The base-case assumptions are classified as follows:

Microgrid parameters

These parameters include: Normative values for the components (gas turbine, PV, wind turbine, and demand response/energy efficiency) of the 10-MW system described above, including the capacity factors and financing costs for each component. Capacity factors presented in Table 6.

Normative values of the microgrid system's distribution grid and the costs of alternative additions to the centralized transmission and distribution network.

Avoided environmental costs

These parameters include: For coal, diesel, and dual-fuel generation: Per-kWh emissions of SO_x, NO_x, CO_2, and particulate emissions as calculated by the Israel Public Utilities Authority. For gas turbines: Per-kWh emissions SO_x, NO_x, CO_2, and particulate emissions as calculated by the US Department of Energy.[6]

Costs per kWh of each emissions type as calculated by the Israel Public Utilities Authority.

The output of the model is a summary of the costs of a microgrid comprised of the components mentioned above and the costs of adding a conventional combined-cycle gas turbine to the existing T&D grid, including any necessary grid upgrades.

The model calculates the annual net benefits from microgrid installation as follows:

Net microgrid benefits = Economic benefits + Reliability benefits + Environmental benefits + Deferred Transmission and Distribution benefits – Additional generation and construction

Each benefit and cost is calculated relative to a "status-quo" assumption, by which expansions to the electricity sector will occur through additional natural gas-fired central station combined-cycle generation and additional transmission and distribution investment.

It should be noted that the revenues from providing energy and ancillary services by a microgrid and a status quo alternative are excluded from the analysis, since it is assumed that the revenues from providing identical quantities of these services would be identical as well. Such an assumption may be reasonable for markets with centralized markets for energy and ancillary services, but may be less valid for markets dominated by bilateral contracts and self-provision. Since the current proposed reforms of Israel's electricity sector include fully centralized markets, the assumption of identical revenues for identical services is reasonable for the timeframe in which microgrids would move beyond an initial "pilot project" stage.

Table 7 summarizes the expected base-case annual costs and benefits associated with 2 investment alternatives: (a) a 10-MW incremental investment in a microgrid; and (b) a conventional 10-MW incremental investment in a central-station combined-cycle gas turbine with the necessary transmission and distribution system additions. The generation and construction costs, which constitute the largest component of the cost-benefit analysis, reflect the total annualized costs of constructing the central-station and microgrid infrastructure, and the associated costs of energy generation under both alternatives.[7] Environmental benefits are calculated as the difference between the environmental costs caused by the microgrid and the environmental costs of a conventional central-station combined-cycle gas turbine.

This analysis indicates that, considering the reliability, T&D investment deferral, local economic, environmental, and social costs and

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[6] US Department of Energy website https://www.eia.gov/electricity/annual/html/epa_a_03.html.

[7] The central-station combined-cycle gas turbine and associated infrastructure were selected for the conventional alternative, since it is highly unlikely that a microgrid resource composition will be different from the resource mix procured by a vertically-integrated utility – unless mandated by the regulator. The combined-cycle gas turbine is still considered for a variety of resource planning studies for new capacity, despite the growing participation by renewables.

Table 5
Assumptions used for calculating the economic multiplier benefits of microgrids.

Salary multiplier (to account for wage increase above average wage)	Microgrid	Status quo
GDP per capita (2016)[a]	$33,117	$33,117
Unemployment compensation (% of average wage)	60%	60%
Average direct salary[b]	$82,632	$82,632
Average indirect salary[c]	$70,556	$70,556
Average California wage (est 2009)[d]	51,671	51,671
Salary ratio of direct to average	1.60	1.60
Salary ratio of indirect to average	1.37	1.37
Job multiplier	1.13	1.13
Salary microgrid - direct	$52,960	$52,960
Salary microgrid - indirect	$45,220	$45,220
US microgrid jobs[e]	14,890	
microgrid MW[f]	1540	
US microgrid direct jobs/MW[g]	9.7	0.8
US microgrid indirect jobs/MW[h]	11.0	0.9
Salary benefits: direct	$5,120,639	$423,682
Salary benefits: indirect	$4,962,473	$406,984
Foregone unemployment compensation	$4,101,761	$337,793
Total annual economic benefit	$14,184,873	$1,168,460

[a] World Bank (2016), https://databank.worldbank.org/home.aspx, Accessed July 11, 2019.

[b] National Renewable Energy Laboratory (2004 and 2019), https://www.nrel.gov/analysis/jedi/using-data.html, Accessed July 11, 2019.

[c] National Renewable Energy Laboratory (2004 and 2019), https://www.nrel.gov/analysis/jedi/using-data.html, Accessed July 11, 2019.

[d] US Bureau of Labor Statistics (2012), http://www.bls.gov/cew/state2002.pdf , Accessed July 11, 2019.

[e] Environmental and Energy Studies Initiative, Fact Sheet - Jobs in Renewable Energy and Energy Efficiency (2017), http://www.eesi.org/papers/view/fact-sheet-jobs-in-renewable-energy-and-energy-efficiency-2017, Accessed July 11, 2019.

[f] Utility Dive (2016), , https://www.utilitydive.com/news/microgrid-capacity-to-exceed-37-gw-by-2020-a-new-study-says/420284/. Accessed July 11, 2019

[g] World Energy Forum (2012), Energy for Economic Growth Energy Vision Update 2012, http://www3.weforum.org/docs/WEF_EN_EnergyEconomicGrowth_IndustryAgenda_2012.pdf, Accessed July 11, 2019.

[h] World Energy Forum (2012), Energy for Economic Growth Energy Vision Update 2012, http://www3.weforum.org/docs/WEF_EN_EnergyEconomicGrowth_IndustryAgenda_2012.pdf, Accessed July 11, 2019.

Table 6
Capacity factors.

Generation	Capacity factor
Solar	20%
Wind	26%
Microturbine	60%
Demand response/efficiency	2%
Battery storage hours per day	1

Adjusted form The Israel Energy Forum (2013).

benefits of each alternative, the net benefits to the Israeli economy from selecting the incremental 10-MW investment in a representative Israeli microgrid exceed $13 million per year.

Note, however, that when the economic multiplier benefits are removed, the results are significantly different. See Table 8.

That is, the benefits from microgrid investments are approximately $259 thousand per year.

For perspective, generation capacity additions by the Israel Electric Corporation have averaged 166 MW from 2008 through 2018, reaching 13,775 MW of installed capacity by the end of 2018. Total annual capital investment has averaged approximately $1 billion since 2015, about $400 million of which has been in the generation sector (Israel Electric Corporation, 2019).

The key sensitivities around these base-case assumptions are:

Levelized costs of microgrid components: The base-case results reflect the lower-range of levelized costs for these components, based on recent survey data. However, the magnitude of the downward trend in microgrid component costs, especially for photovoltaic installations and storage, is difficult to forecast. Moreover, levelized costs are based on assumptions for capacity factors for each microgrid component; capacity factors are likely to increase significantly as well as technologies and materials become more efficient. Therefore, it is possible that the current cost assumptions used in this paper will significantly overstate future microgrid costs.

Environmental costs: As noted above, the base-case results reflect the environmental costs included in ExternE's estimation of marginal damage costs. However, it is possible that these results will be inconsistent with updated marginal damage costs and with market prices for emissions, as these markets become more liquid. The range of sensitivities for environmental costs can vary in both directions around the base case.

T&D deferral costs: While T&D deferral costs are not likely to vary significantly in real terms over the short-to-intermediate term, they are likely to vary significantly across areas. The base-case assumptions use an average systemwide cost that may be one-half to one-third of the deferral costs in a congested urban "load pocket" that requires expensive undergrounding of T&D facilities. To the extent that microgrids would be introduced initially in these urban areas, the base-case analysis will significantly understate the true deferral costs.

Reliability estimates: Value of Lost Load (VOLL) is one metric used to assess incremental reliability values. However, VOLL varies considerably across customer classes and among countries. Moreover, VOLL is likely to rise as changes in end-use technologies and usage are likely to require more reliable systems. We also note that we have not accounted for any resiliency value to microgrids, despite microgrids' ability to preserve reliable electricity supply during low- probability/high-impact events.

Summary of findings and their relation to prior studies

To date, economic analyses of microgrids have adopted a broader focus, mainly due to greater data availability. For example, Morris (2012) explicitly models the value of ancillary services that microgrids can provide to the T&D Company beyond that provided by conventional resources; these services include reactive power/voltage support, black-start, and local operating reserves. Calculations often focus on the ancillary services which microgrids are capable of providing (primarily voltage control and frequency response). However, calculation of this added value uses the cost of additional transmission and distribution infrastructure required to provide this additional energy security – costs that are already included in the measurement of avoided transmission and distribution costs. While it should be possible to determine the variable cost differential between dispatching a microgrid and dispatching another source of ancillary services, the factors involved in calculating "counterfactual" microgrid-related dispatch costs are far too complex to address without a dispatch model capable of incorporating, at minimum, the most significant factors.

The other major differences between this work and the existing literature are in the choices of data sources and the assumptions supporting these choices. For example, rather than using VOLL to determine reliability values based on consumer valuations, other researchers (e.g., Morris, 2012) use the value of regulatory penalties assessed on the utility for un-supply. Others use seasonally- adjusted VOLL to reflect the microgrid's reliability value during peak periods. Moreover, other studies have assumed carbon prices in the range of $20–$30/ton – including Israel's own 2012 Kandel Commission[8] and leading energy consultancies - as compared to $10/ton used in this paper. There are also

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[8] An inter-ministerial committee that examined the Israeli market benefits from electricity produced by renewable energy sources (including benefits of fuel savings, capacity savings, environmental benefits, energy security and insurance, contribution to employment and industry development).

Table 7
Summary of annual costs and benefits of the sample 10-MW microgrid.

	Microgrid	Conventional	Difference
Benefits ($)			
Reliability	1,611,111	0	1,611,111
Avoided T&D	1,523,930	0	1,523,930
Environment	86,048	375,989	289,941
Economics	14,184,873	1,168,460	13,016,413
Total benefits	17,405,962	1,544,449	15,861,513
Costs ($)			
Generation	4,651,594	2,065,271	$2,586,323
Net annual benefits	$12,754,367	–$520,822	$13,275,190

significant differences in other emissions prices. The main differences are the NOx per-ton price of $2400/ton used by the PUA in Israel, versus the $3500–4000/ton assumed in other related literature (South Coast Air Quality Management District, 2017).

It is worth noting that one criticism of the ExternE results is that they have not been updated since 2006. A subsequent analytical tool, the Needs Project, has been developed within ExternE's Impact Pathway Approach and uses many of the same approaches as ExternE, while also reflecting social characteristics of different customer groups in order to develop equity-weighted estimates of marginal environmental damage costs. The current literature uses neither ExternE nor its Needs Project successor, focusing instead on combinations of regulatory decisions and market prices for emissions. Nevertheless, in order to conduct a valuation of environmental costs at the societal level, rather than at a project or utility level, the Needs Project or a similar current tool, should be used. It should be noted, however, that the Needs Project should be updated for 2018 (Anthoff, 2007).[9]

To the extent that emissions markets become more competitive and reflect the social marginal costs of fossil-based electricity generation, the possibility of using such market-based emissions prices rather than estimated values that are heavily dependent upon methodologies and assumptions will contribute significantly to developing accurate, reliable measures of microgrids' environmental benefits.

The findings from this paper are roughly consistent with those of Morris (2012) and other work focusing on valuing distributed energy resources (which microgrids facilitate). The results of that study indicate that, while microgrids may be superior to conventional central-station generation on a stand-alone cost-benefit analysis, both resource types require compensation through some combination of capacity, energy and ancillary service payments. The types of compensation necessary, however, remain a subject for further research, since even most of the existing literature focuses on regulated utilities' receiving revenues based on tariffed rates with a “guaranteed” rate of return on invested capital.

Potential shortcomings/weaknesses in methodology and data sources

In addition to the shortcomings mentioned above regarding ExternE, there are several other methodological concerns that should be addressed in further research. These concerns include:

A need to integrate greater engineering detail on optimal microgrid configuration offering the most efficient combination of services to the grid and microgrid customers. The current model assumes a predetermined microgrid configuration that only offers electric energy.

Improved metrics for evaluating the equity effects of various microgrid configurations. Universal access to a reliable, resilient electricity supply that is facilitated by microgrids at least cost is not addressed in a rigorous, quantitative manner. This paper addresses such equity concerns only by assigning higher weights to residential customers in determining overall Value of Lost Load. This approach does not allow for differentiation among residential customers in terms of their VOLL and their current level of access to reliable, resilient supply.

Recommendations for microgrid policymaking

The primary objective of this paper is to provide an approach to determining the costs and benefits of microgrid integration that is useful for energy policymaking. Despite the simplicity and generalizability of this approach, its usefulness depends largely on the quality of the data inputs and assumptions. Therefore, an extensive review of the relevant data available is strongly recommended. For example, while reliable data on generator's capital and operating costs are widely available, usable information on environmental costs and economic multiplier benefits is often less available, requiring more professional judgement by policymakers and regulators. However, acquiring the knowledge base for such judgement will itself require a broader base of information that is likely gained only through microgrid implementation. Therefore, it is strongly recommended that policymakers incentivize pilot projects for microgrid development that can provide useful information for cost-benefit analyses of proposed microgrid projects. Moreover, policymakers should incentivize existing microgrid developers to provide data on their projects, subject to confidentiality considerations.

Conclusion and directions for further research

This paper is intended to serve as a preliminary basis for quantifying the economic, environmental, and social benefits resulting from microgrid implementation. At this stage, this approach is imperfect for 2 primary reasons: (1) Lack of domestic research on the benefits of microgrid components, such as renewables and demand-response resources, as is currently conducted in the US and Europe; and (2) Lack of domestic experience and resulting analytical work on microgrid expansion. Nevertheless, even in US states such as New York and California, which are recognized as leaders in microgrid development, there is a third deficiency in microgrid valuation: the quantification of social benefits associated with microgrid development. Such benefits must include not only the value of increased reliability, but also the benefits of control over the microgrid as a common-pool resource that would otherwise be relinquished to the T&D utility.

The subject of economic multipliers with respect to microgrid development is also an issue requiring resolution. Currently, such multipliers are controversial for several reasons, including: (1) the inability to trade microgrid services which are inherently local; and (2) the difficulty in estimating local economic welfare improvements in a local area, where most of the infrastructure is constructed and installed by professionals from outside the micro-grid area. Due to the controversy regarding economic multipliers, some of which differ by factors of 5–10, we have chosen to use the most conservative estimates of economic multipliers available for renewable technologies. However, as noted above, multipliers can differ significantly among industries, such that any

Table 8
Summary of annual costs and benefits of the sample 10-MW microgrid - Economic multiplier benefits removed.

	Microgrid	Conventional	Difference
Benefits ($)			
Reliability	1,611,111	0	1,611,111
Avoided T&D	1,523,930	0	1,523,930
Environment	86,048	375,989	289,941
Total benefits	3,221,089	375,989	3,424,982
Costs ($)			
Generation	4,651,594	2,065,271	2,586,323
Net annual benefits	–$1,430,506	–$1,689,282	$258,777

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[9] See also EcoSense website, http://ecosenseweb.ier.uni-stuttgart.de/.

microgrid with a primary customer of a specific industry type can have significantly different economic multipliers.

As noted above, using even the conservative estimates of economic multipliers, the estimated economic benefits of microgrid expansion are significantly larger than the other benefits included in this study. Therefore, developing reliable estimates of economic benefits of microgrid integration for a given region or locality can have significant implications for policymakers.

In addition, a useful area for further research is quantification of microgrids' effect on resilience. Such quantification is starting to come together, as a result of an unusually high number of high- impact natural disasters in recent years. However, rigorous statistical work based on these events and simulations complementing these events have yet to yield an accepted method for quantifying the additional resilience that microgrids may provide.

Another area requiring more sophisticated modeling and research is scenario development regarding technological development for microgrid components. Current estimates and ranges around these estimates do not reflect the entire set of possible cost trajectories, even for the next several years. It is possible, even likely, that our estimates of microgrid costs will significantly overstate future costs. Such scenario development should reflect the conditions during each implementation year, given the rapid projected declines in microgrid component.

Finally, we are not aware of any work that quantifies the effect of microgrids' promoting a “virtuous cycle”, whereby microgrid growth featuring storage, combined heat & power, renewables, and demand response will yield cost declines in each of these components, and will thus stimulate greater demand for microgrids with these components.

Therefore, it is fair to state that this paper provides an initial point estimate of the costs and benefits of microgrids and conventional generation interconnected to a centralized grid. However, further research is needed, both in modeling changes in technology and its associated costs, and in modeling social benefits associated with microgrid development.

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