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The impact of policy on microgrid economics: a review

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ABSTRACT

This paper investigates the impact of government policy on the optimal design of microgrid systems from an economic cost minimization perspective, and provides both an overview of the current state of the art of the field, as well as highlighting possible avenues of future research. Integer programming, to select microgrid components and to economically dispatch these components, is the optimisation method of choice in the literature. Using this methodology, a broad range of policy topics is investigated: impact of carbon taxation, economic incentives and mandatory emissions reduction or mandatory minimum percentage participation of renewables in local generation. However, the impact of alternative tariff systems, such as capacity tariffs are still unexplored. Additionally, the investigated possible benefits of microgrids are confined to emissions reduction and a possible decrease in total energy procurement costs. Possible benefits such as increased security of supply, increased power quality or energy independence are not investigated yet. Under the expected policy measures the optimal design of a microgrid will be based on a CHP-unit to provide both heat and electricity, owning to the lower capital costs associated with CHP-units when compared to those associated with renewable technologies. This means that current economic analyses indicate that the adoption of renewable energy sources within microgrids is not economically rational.

KEYWORDS

Microgrids, Policy Impacts, integer programming, Policy analysis

Nomenclature			
$C_{th,f}$	Fuel cost of a conventional thermal unit	E_{en}	Emissions associated with own electricity generation
$C_{chp,f}$	Fuel cost of a CHP unit	E_{grid}	Emissions associated with grid-bought electricity
$C_{boil,f}$	Fuel cost of an auxiliary boiler	β	Weighting parameter
C_{grid}	Costs of power transactions with the grid		
C_{stor}	Costs of storage		

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C_{shed}	Costs associated with load shedding		
C_{en}	Net costs associated with energy transactions		
C_{op}	Operational costs		
C_{tax}	Carbon taxation costs		
Inv_{tech}	Capital costs of installed technology		

1 INTRODUCTION

Various factors are driving the adoption of smart grids [1]. One of these is certainly the desire to move to a low-carbon energy future [2]. Previous work has however reported on the uncertainty surrounding both the economics of distributed energy generation [3] and the environmental impact of smart grids [4]. Additionally, it is expected that policy measures will be needed to pave the way for the transformation of the current grid into a smart grid and for the adoption of renewable energy systems [5].

One promising approach with regards to the decarbonisation of the energy system is the adoption of microgrids as basic building blocks for the construction of a smart grid. Microgrids encompass both heat and electric load [6] and are tailored towards the integration of distributed generation [7], including renewables. Microgrids also offer the possibility of increasing power quality and reliability [8].

Before presenting an overview of the various microgrid configurations reported in the literature, it is useful to first define what a microgrid actually is. Lasseter et al. present a microgrid in [6] as a grouping of loads and thermal as well as electrical power sources. Additionally, the microgrid must have a sufficient amount of flexibility to operate as an aggregated system, meaning it acts as a single controllable load with regards to the distribution system. Lidula and Rajapaska base their definition of a microgrid more strictly on the physical components when they define a microgrid in [7] as a “variety of distributed generators, distributed storages and a variety of customers loads”. They additionally stipulate that it is “a portion of an electric power system located downstream of the distribution substation”. Lo Prete et al. expand on these definitions, as they state that a microgrid should not only be able to operate as part of a larger grid, but also autonomously in islanded mode [9]. This is a slight variation of the definition as given by IEEE [10], their definition encompasses the ability to operate in islanded mode, the clustering of generation and demand that operates as a single controllable entity, but also stipulates that this entity needs to have clearly defined electrical boundaries. In [11], Siddiqui et al. explicitly build on the definition provided by Lasseter et al. in [6] by stipulating that microgrids will be able to tailor power quality and reliability to the requirements of the served loads.

While the above discussion shows that both the inclusion of heat supply and demand as well as the ability to operate in islanded mode are not always explicitly included in the definition of a microgrid, this paper will utilize the broadest definition of a microgrid, meaning a system consisting of generation and consumption of heat and power, that is able to operate as a part of a larger system or in islanded mode and which can include distributed generation, while providing sufficient power quality and reliability to the included loads. It is important to note that none of the above definitions, appart from the one of Lidula and Rajapaska [7], explicitly mention storage as being part of a microgrid. However, storage is implicitly included by specifying that a microgrid should be able to operate in islanded mode: depending on which heat and power generation methods that are chosen, the economically optimal microgrid configuration will include storage components for heat, electrical power, or both.

While it may seem at first that microgrids are only attractive for electrifying off-grid communities, such as reported in [12], where microgrid designs are investigated for remote communities, there is most certainly a place for grid connected microgrids as well. Prehoda et al [13] consider PV-powered migrogrids as a vital tool to safeguard security of supply from natural disasters as well as electronical and physical attacks. Furthermore, Coelho et al. [14], investigate microgrids as an important building block in the interconnected smart cities of the future.

Where the economics of the installation and operation of macrogrid-connected microgrids are concerned, there are two important actors: the owner or operator of the microgrid on the one hand, and the utility to which the microgrid is connected on the other hand. It is important to note that these two actors have different goals: the owners of a microgrid will strive for economically optimal operation, meaning the minimisation of operating, energy and capital costs over the lifetime of the microgrid, whereas the utility on the other hand is more concerned about voltage stability and overall reliability of the macrogrid. These differing goals also directly translate into different research approaches: papers focussed on the microgrid owner or operator [11,15-20] are primarily concerned with the costs associated with operating the microgrid, with policy interventions, such as taxes, being treated as another cost. The papers focussing on the utility as an actor however [9,21] investigate methods to incentivise microgrid behaviour that is favourable for the stability and power quality in the macrogrid, meaning that the focus is not on whether a microgrid is economically feasible or not, but on the effectiveness of the policy measure under review in steering the microgrid behaviour towards the desired outcome.

It should be noted that this review is exclusively focussed on microgrid economics and as such does not touch upon the technical aspects of microgrids. These topics have been exhaustively covered in previous research: see the discussion presented by Mariam et al. in [22] for an overview of the different types of microgrid architectures that have been deployed in test beds or the classification based upon functional layer presented by Martin-Martines[23] for more in depth technical reviews related to the subject of microgrids.

To realise the reported benefits offered by microgrids [6,8] it seems that the uncertain economic outcomes of smart energy systems in particular when faced with competition from the macrogrid with its advantageous returns to scale [3,4], will have to be overcome by policy intervention in order to enable microgrids to be an economically viable alternative to the macrogrid. Hence, the contribution of this paper is to review the investigations of impact of government policy on the optimal design of microgrid systems from a cost minimization perspective. Specifically, the objectives of this review are threefold: firstly, we provide an overview of the current state of the art of the field with regards to used methodology. Secondly, this review will explore if there is a research gap in the domain of the economics of microgrids and thereby provide valuable avenues for further research. Finally, we investigate if there is a growing scientific consensus where expected technical make-up of microgrids under common policy interventions are concerned.

After giving an overview of adopted methodology in the literature, this paper elaborates on the policy measures investigated in the literature. A fourth section reviews reported results in literature. A section discussing these results and providing possible avenues of further research concludes this paper.

2 METHODOLOGY

Based on the definitions provided above, only papers discussing microgrids that take into account both electrical and heat demand are considered in this review. This, in combination with the constraint that all considered papers must include the economic analysis of at least one policy intervention, led to the inclusion of 8 papers published through the Web of Science.

The methodology of all reviewed papers is similar: all use mathematical optimization based on mixed integer programming combined with simulations, to simulate the impact of policies and technology options under review on the economics of operating a microgrid, or to analyse the impacts of policy measures on the interactions between microgrids and the macrogrid. There is, however, some difference when it comes to the valuation of externalities, environmental or macrogrid related, in these models: the most common approach focusses on the environmental externalities, in which case the approach of choice is internalisation via the use of carbon taxation [11,16,17,19,21]. The advantage of this approach is that it provides an explicit valuation of carbon emissions, and allows for the analysis of the impact of varying the price per emitted ton. However, this approach also means that all other externalities are implicitly said to be of no consequence. Schreiber et al. [21] adopt a variation on this approach: they investigate the impact of a more flexible tariff system on the use of demand response and household costs. No externalities are considered, but the base case, consisting of a non-flexible tariff system is compared with the flexible tariff system. Other authors use multi-criteria methods [18], or evaluate the simulation outcomes using varied indicators to incorporate externalities [9,15].

2.1 Objective functions and decision variables

Reference	Objective(s) to be minimised	Decision variables	Simulation horrizon
Operational models			
[18]	$\sum C_{th,f}+C_{chp,f}+C_{boil,f}+C_{grid}+C_{stor}+C_{shed}$ $\sum E_{en}+E_{grid}$	hourly set-points	24 hours

[15]	$(1-\beta)(\sum C_{en}+C_{op}+C_{tax}) + \beta(\sum E_{en}+E_{grid})$	hourly set-points	24 hours
[9]	System approach – see discussion		Hourly, extrapolation to yearly cost based on 6248 hours, divided into 6 blocks
Investment models			
[17]	$\sum C_{en}+C_{op}+ C_{tax}+Inv_{tech}$	Installation and capacity of considered technologies, hourly set-points	1 year
[11]	$\sum C_{en}+C_{op}+ C_{tax}+Inv_{tech}$	Installation of technologies, hourly set-points	1 year
[19]	$\sum C_{en}+C_{op}+ C_{tax}+Inv_{tech}$	Installation and capacity of considered technologies, hourly set-points	1 year
[20]	$\sum C_{en}+C_{op}+ C_{tax}+Inv_{tech}$	Installation and capacity of considered technologies, hourly set-points	20 year lifetime of project
[16]	$\sum C_{en}+C_{op}+ C_{tax}+Inv_{tech}$	Installation and capacity of considered technologies, hourly set-points	1 year of simulated set-points to extrapolate energy supply costs over 20 year microgrid lifespan

Table 1- Optimisation objectives and decision variables

Table 1 provides a structured overview of the optimisation objective function, the decision variables and the simulation horizon used in each of the reviewed papers. As is readily apparent from the table, for reasons of clarity and ease of comparison, a succinct and high-level summary is provided. The technical details are of course discussed in more detail in the individual papers, but for the purposes of this review, the modelling discussion will be restricted to the similarities and differences in the reported approaches. Table 1 clearly shows that the approach of the papers concerned with investment decisions in microgrid design are homogenous: all of them take the energy costs, which is to be understood as the net cost or benefit arising from energy transactions with the macrogrid, the operational cost, including maintenance and fuel costs where applicable, of selected technologies, emissions taxation and annualised capital costs into account. The decision variables in these papers are also similar: from an investment standpoint, the installation and sizing of each considered technology is considered, except for in the work of Siddiqui et al. [11] where applicable technologies are of fixed size, meaning only whether or not they are included is decided upon. Both the papers focusing on investment decisions and those investigating purely operational decisions use the hourly setpoints of applicable installed technologies as well as hourly interactions with the macrogrid as decision variables. The reviewed papers do differ from one another regarding technologies they consider for adoption in a microgrid, as will be discussed in section 3, technology and policy. Lastly, the similarities between the investment oriented papers also extends to the choice of simulation horizon, four of the references evaluate the obtained results over the course of one year. Zachar et al. [13] additionally extrapolate the obtained simulation results to the expected lifetime of a microgrid of 20 years, while Yu et al [17] look at the entire 20 year expected life time of the considered microgrid.

The reviewed papers focusing on only the operational decisions involved in the economic operation of a microgrid are, while more varied, still in overall consensus where methodological approach is concerned. Both [12] and [15] take the short run operational and emission costs into account. They do however slightly differ in the exact definition of those short run operational costs: Aghaei & Alizadeh [15] take only fuel costs into account, while Rocha et al. [12] additionally also include maintenance cost. Furthermore, from among all of the models reviewed, only the model of Aghaei & Alizadeh [15] allows for the possibility of load curtailment. It should also be noted that an inclusion of an explicit carbon price would bring the models of these two papers closer to the approach utilized in the investment analysis models. Finally, the approach used by Lo Prete et al. [9] explicitly focusses on a system approach, as the total cost of an entire distribution system, including microgrids, is minimised. Cost allocation to individual actors or components is not discussed and marginal cost functions for the microgrids are considered to be fixed, meaning it is impossible to interpret the reported results in terms of optimality of individual microgrids.

As can be seen from the listing of the optimization objectives in table 1, only energy procurement costs and environmental impacts –through carbon taxation- are valuated in most of the reviewed papers, even though power quality, power systems reliability and energy independence are also listed as possible benefits offered by microgrids [8]. Only Lo Prete et al. touch upon this, by calculating two reliability indicators [9], the loss of load probability (in outage hours per 10 years) and estimated loss of electricity (in MWh per year). However, as noted before, this analysis is only carried out on the level of the distribution grid, meaning these reliability indicators are not valued at the level of an individual microgrid.

2.2 Simulation set-up

	Demand		Base case			Simmulated location	Year of analysis (publication)
	Heat	Electricity	Heat tariff	Electricity tariff	FIT (Feed-in tariff)		
[15](a)	1.6 MWh	0.77 MWh	0.0523€/kWh (natural gas)	0.1426€/kWh	0.1758€/kWh$_e$ (CHP)	Spain, Europe	(2015)
[15.](b)	Not specified	0.5 MWh	0.0803€/kWh (district heating)	0.1500€/kWh (purchase)	0.0800€/kWh (sale)	Austria, Europe	(2015)
[18]	1.6 MWh[1]	558 kW (peak load), 10,0 MWh[2]	Not specified	Not specified	Not aplicable	Generic	(2013)
[17]	18.5 MWh[3]	12.0 MWh[4]	Not specified	Not specified	Not specified	Greece, Europe	(2014)
[11]	Not specified	4755.0 MWh	Not specified	TOU 0.0528$/kWh (winter off-peak) 0.1005$/kWh (summer on peak)	Not aplicable	California, USA	1999 (2004)
[19]	51.0 MWh	32.0 MWh	0.0540€/kWh (natural gas)	0.1100€/kWh (purchase)	0.08785€/kWh (CHP) 0.5500€/kWh (PV)	Greece, Europe	(2013)
[20]	70 MW (peak load)[5]	48 MW (peak load)[6]	Not specified	Not specified	Not specified	Taichung Industrial Park, Taiwan	(2016)
[16]	1788.5 MWh	03650.0 MWh	Not specified	Not specified	none	Ontario, Canada	(2015)

Table 2 – Simulation set-up

Table 2 provides an overview of the specific simulation set-ups that were used in the reviewed papers. Apart from one reference [18], all are based on real world locations: 1 in Canada, 1 in California, 3 in the South of Europe (Greece and Spain) one in central Europe (Austria) and one in Asia (Taiwan). The sizes of the considered microgrids vary considerably: some of the studies look at a single building, such as both sites considered by Rocha et al. [15] and the hotel considerd by Anastasiadis et al. [17]. Mehleri et al. [19] investigate a cluster of 5 interconnected buildings, Siddiqui et al. [11] look at a total of 69 interconnected sites, Yu et al. [20] consider an entire industrial zone and lastly Zachar et al. [16] consider the energy needs of an entire town. This spread in sizes means that many possible sizes have been considered, but it does also mean that the results can't be all that readily compared to each other. Another factor that impedes easy comparison is the large spread on energy tariffs across the reviewed papers. Year of publication, and when mentioned, the year considered for the simulation is reported for each paper as well, as the examined timeframe might impact both the energy and technology prices. When no specific year for the simulation is mentioned in the reference, the year of publication is used. Table 2 shows that all but one of the reviewed papers fall within a four-year period, from 2013 to 2016, the exception being [11], with a simulation set in 1999.

	Wind turbine	Photovoltaic		Conventional thermal unit		CHP		Gas boiler		Electric boiler	Heat storage	Electric Storage	
		Cost	Rated power (kW)	Cost	Rated power (kW)	Cost	Rated power (kW)	Cost	Rated power			Cost	Rated power
[11]		8650$/kW 7450$/kW 6675$/kW 6675$/kW (20)	5 20 50 100	1730$/kW 970$/kW 833$/kW 1185$/kW 936$/kW (12.5)	25 55 100 215 500	1333$/kWe (12.5)	30	1185$/kW 936$/kW (12.5)	215 500			3960$/kW (12.5)	200
[16]	3400$/kW (20)	5000$/kW (20)				3600$/kWe (20)		60$/kW (16)		60$/kW (16)		132$/kWh (5)	
[17]	No specific data reported, used Bailey et al. [24] as reference												
[19]		4305€/kWp (20)				1583€/kWe 911€/kWe 835€/kWe 653€/kWe 650€/kWe (20)	1 5 10 15 25	760€/kW (20)			25€/kW (20)		
[20]	Uses data presented in [25]												

Table 3 - Technology capital costs (with assumed lifetime in years)

1 Estimated, based on heat demand graph in reference [15]

2 Estimated, based on power generation graph in reference [15]

3 Estimated, based on heat demand graph in reference [14]

4 Estimated, based on power generation graph in reference [14]

5 Estimated, based on power demand graph in reference [17]

6 Estimated, based on heat demand graph in reference [17]

	Wind turbine	Photovoltaic	Conventional thermal unit	CHP	Gas Boiler	Electric Boiler	Heat Storage	Electric Storage
[11]		14.300$/kW 14.300$/kW 12.000$/kW 11.000$/kW	26.500$/kW +0.003¢$/kWh	5.000$/kw +0.015$/kWh 7.500$/kW +0.015$/kWh				0.015$/kWh
[15]	No data reported							
[16]	0.005/kWh	52.000$/kW		0.020$/kWh + 10$/startup	0.8008$/kWh	0.8008$/kWh		0.0014$/kWh
[17]	No data reported							
[18]	No data reported							
[19]		12.30330€/kWp +0.015 €/kWh		0.027€/kWh	0.027€/kWh		0.001€/kWh	
[20]	Uses data presented in [25]							

Table 4 - Technology yearly maintenance and operational costs

Capital and operating costs are listed in tables 3 and 4 respectively. Reference [11] in particular goes into much technical detail with regards to generating technologies, as discrete units are considered, each with their own fuel efficiencies and specific operational characteristics, which accounts for the numerous entries in the tables. The other reviewed papers choose to linearise the available generating technologies, meaning that generation and storage capacity, if applicable, can be had in a continuous spectrum. One exception to this rule is the CHP in [16], where one fixed sized is considered. Higher installed CHP capacity is then achieved by installing multiples of this unit. There is a rather large discrepancy between the costs for gas boilers between [16] on the one hand and [15,19] on the other hand. It should however also be noted that the heat demand considered in [16] is several orders of magnitude greater than that in [15,19], as shown in table 1. Where installation and capital cost data is concerned, [17] directly refers to the work of Bailey et al. in [24]. However, in [24], various sizes and makes of each technology option is discussed, while it is not clear which model is selected in [17], meaning the installation costs in [17] remain unclear. In a similar vein, Yu et al. [20] reference Ren and Gao [25] for the specifics on the selected equipment used in their model.

3 TECHNOLOGY AND POLICY

	No additional policy intervention	Carbon taxation	Minimum autonomy	Economic incentives	Emissions cap	Minimum renewables	Time of use pricing
Macrogrid connected	[9],[15],[16],[17],[20]	[9],[11], [15],[16], [17],[18], [19], [20]	[16], [20]	[15],[16],[17],[19]	[16]	[16]	(11),[18]
Islanded operation			([16])				
Wind Turbine	[16],[20]	[16]	[16], [20]	[16]	[16]	[16]	
Photovoltaic	[9],[16],[17], [20]	[9],[11],[16],[17],[19]	[16], [20]	[15],[16],[17],[19]	[16]	[16]	([11]),[18]
Conventional thermal unit	[20]	[11]	[20]				
CHP	[9],[15], [16],[17], [20]	[9], [11],[15], [16],[17], [19]	[13],[16]	[16],[17],[19]	[15]	[16]	([11]),[18]
Gas Boiler	[15], [16]	[15],[16], [19]	[16]	[16],[19]	[16]	[16]	[18]
Electric Boiler	[16]	[16]	[16]	[16]	[16]	[16]	
Solar Thermal				[15]			
Storage (Heat)	[20]	[19]					
Storage (Electric)	[16], [20]	[11], [16],[17], [18]	[16],[20]	[16],[17]	[16]	[16]	([11]),[18]
Demand response	[9]						[15]

Table 5 – Technology and policy Matrix

Table 5 provides an overview of the different simulation set-ups available in the literature: the columns list applicable policy interventions, while the rows show which technologies were considered in the respective papers. While the reviewed papers usually simulated combinations of various technologies, it is important to note that possible policy interventions were mostly simulated separately, meaning that interaction effects are never explicitly investigated. In some cases, however, multiple policy interventions are present at the same time, both [17] and [19] investigate the impact of carbon taxation, but against the very specific backdrop of a setting that highly favours PV through FIT. Additionally, the analysis conducted in [11] includes a time-of-use tariff, but the impact of this tariff is never explicitly investigated. Aghaei & Alizadeh. in [18] approach the research problem from a different direction: in their simulation, there is both a carbon tax and real-time pricing, and three possible technology configurations are investigated against this backdrop.

3.1 Technologies

The working principles of the technologies listed in table 5 is outside the scope of this review. However, two important observations can be readily made from this table: firstly, most research attention is directed towards the electrical side of a microgrid: only one publication looks at solar thermal panels and one publication at heat storage. This does not mean that heat demand is neglected: as evidenced by the inclusion of CHP in the majority of reviewed papers, the total energy consumption of the microgrid is investigated. This focus on the electrical side of the microgrid does mean that there are no analyses on the trade-off between electrical and thermal storage, in all but one paper only electrical storage is considered, while heat demand must always be instantaneously met. Secondly, while the ability to operate in islanded mode is one of the frequently mentioned advantages of a microgrid, it is not one that has been subjected to any economic scrutiny.

3.2 Policy measures

While the selected technologies are self-explanatory, this is less the case where the researched policies are concerned. This section will therefore provide a discussion of how the various policies have been implemented in the simulations being reviewed.

3.2.1 No additional policy measures

This is the business as usual alternative, and always used as a base case scenario, allowing for the impact of other policy interventions to be estimated.

<u>3.2.2 Market-based policies</u>

3.2.2.1 Carbon taxation

As can be seen from table 5, this is the most researched policy intervention. As mentioned in section 2, methodology, the goal of this policy is to arrive at carbon abatement through the internalisation of the societal costs associated with the emissions of CO_2. It is important to note that both self-generated electricity, where applicable, and electricity bought from the grid are subject to the emissions taxation, for grid-bought electricity, this is added as an extra charge on the electricity bill. Zachar et al. [16] investigate the impact of a carbon price of $30 per ton CO_2, while in [17] a price ranging from €15 to €20 in increments of €0.5 per ton CO_2 was considered. Siddiqui et al. in [11] investigate a wider price range: their simulations study a carbon price ranging from $0 to $1000 per ton in increments of $100 per ton. The scopes of [15,19] are more limited when it comes to carbon taxation: [19] prices emitted CO_2 at €17 per ton and [15] investigates the impact of a carbon tax of €20 per ton of CO_2. This shows that the consensus expected price for carbon emissions is somewhere around €20 per ton, which is in line with the Committee for Climate Change's predictions, forecasting a price of €20 per ton by 2050 [26]. In [20], carbon taxation is investigated in a range centered on $ 0.06, unfortunately, it is not mentioned per which amount of weight this $ 0.06 will be levied, making it difficult to include the reported results in the comparison presented below in a meaningful way.

3.2.2.2 Economic incentives

This is in itself a broader array of policy measures, as tax-related incentives, subsidies or beneficial feed-in tariffs for "green" electricity are all possibilities. Furthermore, these policies can also be targeted to a specific technology. Rocha et al. investigate the impact of a feed-in tariff of €0.1758/kWh_e and €0.1812/kWh_e for CHP and PV respectively [15]. In [16], tax incentives amounting to 30% and 50% of the total installed cost of PV and wind energy are investigated. No specific implementation of these tax incentives is discussed, but for the purpose of the simulation, it suffices that the effect, regardless of implementation, is to reduce the overall cost of installing renewable energy sources by the stated amount.

3.2.2.3 Time of use pricing

The impact of time of use pricing is investigated in [15,18]: Aghaei & Alizadeh [18] opt for a real-time pricing scheme, with the price fluctuating on an hourly basis between $1.7/kWh and $4.2/kWh, according to a predetermined scheme. Rocha et al. [15] study the effects of a time of use tariff structure using time blocks: electricity is priced at €0.1601/kWh between 7:00 and 14:00 as well as between 17:00 and 20:00, €0.1513/kWh between 14:00 and 17:00, and 0.1405/kWh otherwise. The impact of other tariff systems on microgrid economics and optimal design is not investigated.

3.2.3 Command and control policies
As table 5 shows, only one paper researches the impact of various non-market based policies. As the three investigated polices are all quite similar in implementation, they will be jointly discussed. Zachar et al. [16] investigate a level of minimum autonomy, to be understood as a minimum percentage of energy produced by local sources, a limit on the annual CO_2 emissions, implemented as a percentage-wise reduction from a base case, and lastly a minimum percentage of power generated from local renewable sources. Each time, the policies are simulated in 5% increments between 0% and 100% of the mandated policy. In order to facilitate a good understanding of the reviewed results, it is important to note that Zachar et al. [16] have set up their work in such a way that this minimum autonomy is the base case to which the other policy interventions are compared, meaning that the optimal microgrid design, given a certain policy intervention and a pre-determined autonomy level is investigated. Yu et al. [20] only look at a minimum autonomy level using five distinct scenarios. Each scenario defines the minimum percentage of heat and power load that the microgrid is obliged to serve, starting from 10% and progressing to 50% in 10% increments [20].

4 REPORTED RESULTS

This section will summarise the research results of the reviewed papers. After a discussion of the simulation results without policy interventions, the remainder of the reported results are grouped by policy intervention, allowing for the expected outcomes of each policy intervention to be discussed.

4.1 Business as usual

Zachar et al. start their results with the results of an optimisation run with no constraints on installed technology, or required autonomy levels [16]. The results show that no microgrid technology is installed: all required power is bought from the macrogrid, and natural gas combustion in boilers is used to fulfill heat demand. They also investigate a minimum autonomy requirement, which is used as a base-case microgrid configuration which serves as a comparison for the microgrid configurations obtained under the considered market based policies. CHP-units in combination with power purchases from the macro grid are used in this case, with token amounts of wind power (never more than 5% of total power generation) at the 40% and 80% autonomy scenarios, as in each of those cases the installed CHP-units are working at full capacity. Additional CHP-units are installed at the 45% and 90% autonomy levels.

4.2 Carbon taxation

A first interesting result shared between a number of reviewed papers [11,15,16] is that carbon taxation at the expected level does not noticeably impact the technology selection of the microgrid. As a direct result, the carbon taxation does not result in any significant emission reduction compared to the microgrid running without carbon taxation being present, meaning the only real result is an increase of total energy costs for the microgrid. The reason for this behaviour is that, at realistic carbon taxation levels of between 15€ to 25€ per ton, the carbon price is simply too low to offset the high capital costs associated with carbon-free generation technologies such as wind turbines and PV-panels. Siddiqui et al. [11] also investigate the impact of a higher level of carbon taxation, and only when the price of carbon reaches 900$ per ton does it incentivise the installation of PV-panels, according to the results presented in [11]. Such a carbon price is however far above even the most pessimistic forecasts of the Interagency Working Group on Social Cost of Carbon, which prices the social cost of carbon in 2015 to be below 105$ per ton with 97% certainty [27].

The two papers reporting on simulations in a Greek setting however, have noticeably different results: both in the works by Anastasiadis et al. [17] and Mehleri et al. [19] the simulation results indicate the heavy adoption of PV. This is however not in contradiction with the results reported by other authors, as the examined situation can be considered to be a fringe case, owning to the extremely favourable FIT for solar panels (0.55€/kWh as reported in [19]), meaning the high capital cost of PV-panels is strongly mitigated in such a setting. Even in these cases, CHP units are still part of the system, accounting for 23% of the installed capacity and supplying about 50% of the energy demand in the microgrid in [19].

Interestingly, Yu et al. [20] report outcomes that deviate from the results discussed above: their simulation results indicate that, for the case they considered, the optimal system is made up of a balanced mix of internal combustion engines and solar PV, with each accounting for half of the installed capacity. Yu et al. attribute this to the fact that solar PV does not require any fuel for operation, and the year-round sunny weather in the location they study [20]. No data is provided by Yu et al. in [20] on the amount of energy provided by the various technologies installed, and hence we have no insight into the utilization of each of the retained technologies.

4.3 Economic incentives

The reviewed papers show that economic incentives can certainly have an impact on the economic optimal microgrid configuration: Zachar et al. [16] investigate the impact of both a 30% and a 50% tax credit towards renewable energy investments. Their results show a rather limited impact for a 30% tax credit, but a far more appreciable impact for a 50% tax credit: in the case of a 30% tax credit only a token amount of energy is procured from wind power, never surpassing more than 5% of total energy supply. A tax credit amounting to 50% of investment cost for renewable energy however incentivises the adoption of wind power a lot more: not only does it delay the installation of a first CHP-unit until 20% local autonomy is demanded, this level of tax credit also assures that up to one third of the total power generation is sourced from renewable sources. It should be noted that the adoption percentage of renewables under this scenario is not monotonously increasing with the requested autonomy, it is rather dependent on the number of CHP-units installed, and shows a jump downwards whenever an additional CHP-unit is installed. However, even under a 50% tax credit scheme, CHP-units still contribute the dominant share of locally generated power to the microgrid, except at the 5% to 15% autonomy levels, where only wind power is installed. The impact on emissions of a tax credit is reported to be once again dependent on the height of the tax credit, with only a 50% tax credit being able to motivate microgrids to achieve meaningful emission reductions of between 5% and 25% of emission when compared to the buy all from macrogrid scenario, depending on the desired autonomy level. The reviewed papers which research the effects of FIT's are unanimous in their findings: in the papers where the configuration of the generating capacity is optimised, the technology favoured by the FIT is adopted: in [19] PV is installed up to the maximum allowable capacity (10 kW per building) as defined by legislation. In [15], set systems configurations are tested, but the effect of the FIT is more dependent on the height of the FIT in comparison to the electricity rate: when the FIT is higher than the purchase price of electricity, all locally generated electricity is sold back to the macrogrid, and all the required power is bought from the macrogrid. When the line losses this incurs are considered, this is clearly a suboptimal solution.

4.4 Tariff systems

Rocha et al. find that switching to a TOU-tariff has negligible impact on their obtained results [15]. Aghaei & Alizadeh [18] find that the impact of real-time pricing combined with carbon taxation works in two directions: under such a scheme generation costs fall when demand response and energy storage are implemented in a CHP-powered microgrid, while emission costs rise. When only energy storage is incorporated, however, energy costs rise slightly while emission costs rise even higher, showing that energy storage is in itself not economically viable.

4.5 Command and control policies

Zachar et al. [16] show that both an emissions cap scenario or a minimum renewable scenario are the most effective ways to mitigate carbon emissions. As can be expected, an emission cap scenario is most effective at capping emissions at a selected target level. However, this comes at a steep cost to the microgrid: total energy procurement costs are double those of the reference scenario at 50% emissions reductions, and rise to seven times the cost of the reference scenario at 100% of emissions reduction. This is also the only scenario investigated by Zachar et al. [16] where the amount of power from CHP-units decreases as the investigated scenario variable, i.e. emission reduction, goes up: at 5% emissions reduction, 30% of the required power is generated by CHP while the rest is bought from the macrogrid. Renewables integration starts at 10% emissions reduction, with the installation of 5% of wind power, and renewables become the dominant power source at a mandated emission reduction of 45%.

The minimum renewables scenario of Zachar et al. [16] is the only set-up of all the reviewed papers where the result of the optimisation does not include CHP-units. In this scenario, all the power generated by the microgrid will originate from renewable sources. This also means that the emissions associated with the energy consumption of the microgrid fall at a steady pace as the minimum percentage of renewables is increased. As was the case with the previously discussed command and control intervention, this too comes at a cost for the microgrid, as costs quickly rise when compared to the base case.

5 DISCUSSION

This section discusses the reported findings in the literature. A first part of the discussion aims to synthesize the above reported results into general trends concerning both the considered technologies and policy measures, while a second part delves more deeply into recommendations for further research.

When reviewing the results reported in the literature, it is immediately apparent that the scientific consensus strongly favours the adoption of CHP-units in microgrids: not only are they included in all but one of the optimal solutions of each of the reviewed problems, CHP-units are also the most prominent energy provider in the microgrid. The reason for this is always the high capital costs associated with renewable energy generation technologies. This means that the often-heard benefit of microgrids, enabling greater integration of renewable energy sources, is not really supported by the economic analyses that have been carried out, as renewable energy sources only become economically attractive when they are heavily favoured by policy measures, either through market based interventions such as tax credits or generous FIT's, or through non-market based command and control policies by the imposition of an emission cap or a minimum renewable requirement when it comes to power generation.

This favoured adoption of CHP-based microgrids is also stable through time, as CHP-units are part of the solution found for 1999 by Siddiqui et al. [11] as well as being the staple in the optimal solution reported on in 2015 by Zachar et al. in [16]. Considered against the backdrop of the price of PV-panels which fell by 80% over the considered timespan [28], this seems to indicate that there are other barriers to the adoption of PV-systems in microgrids in addition to the significant capital costs associated with installing PV-panels. This conclusion is further substantiated by the observation that PV-panels are only installed on a large scale in those scenario's where they are specifically targeted by policy measures. Such measures can bias the choices available to actors, e.g. generous feed-in tariffs for electricity produced by PV-systems as was the case in [10]. Alternatively, such policy measures can restrict the choices available to actors, such as a mandated emissions reduction, or an obligatory minimum stake of renewables, both investigated in [16].

Electricity from wind turbines is investigated in only two of the reviewed papers [16,20]. This is not exactly surprising, since wind turbines offer too much generation capacity to be considered for inclusion in most microgrids, which explains why they were included in [16], as this was by far the largest microgrid, encompassing an entire town. Based on the reported results, wind turbines prove themselves to be the more economically viable renewable electricity source when compared to PV-panels. This means that the sizing of a microgrid is possibly not as straightforward as it seems: in all the reviewed papers, the considered microgrids are of fixed size, with the heat and power demands being treated as givens. However, the reported results in [16] with regards to the adoption of wind turbines indicates that there are possibly economies of scale waiting to be realised. The findings reported in [20] seem to contradict the results of Zachar et al. [16] as no wind turbines are part of the reported solution. However, Yu et al. [20] report that the reason behind the non-inclusion of wind turbines is that the local wind speeds at location considered were too low.

The unattractiveness of renewables from a purely economic standpoint is clearly shown by Zachar et al. in [16], as the total costs for the microgrid increase the more the adoption of renewables within the microgrid is enforced through government intervention. These costs are not as readily apparent in the scenario's using FIT's or tax incentives due to the scope of the analyses: the focus is always on the costs and benefits accrued by the owner or operator of the microgrid, while in these scenario's, the costs of the adoption of renewable energy sources will be borne by society as a whole through levies or taxes.

The observation that CHP-units will only be replaced by renewable energy sources if the carbon prices were to rise far above the expected societal costs of carbon means that from a purely economic point of view, it is better to continue to burn fossil fuels while compensating the damage to society through payment of a carbon tax, than to switch to renewable energy generation, considering the current state of technology and the current estimates of the societal costs of carbon. Additionally, the amount of emission reductions realised by the adoption of CHP-powered microgrid is highly dependent on the energy mix used to power the macrogrid, indicating that the expected environmental impact of microgrid adoption remains unclear.

It is also interesting to note that the discussion of the environmental impacts due to the generation of electricity is narrowed to the emission of carbon, which is then remedied via carbon taxation. However, the generation of electrical energy also has other potential externalities on human health [29], such as the emmissions of other greenhouse gasses such as CH_4 and N_2O or air pollutants such as SO_2 or NO_2. Work has been done on trying to determine the costs of these externalities by Shindell in [30] and it stands to reason that the inclusion of these costs in a way analogous to carbon taxation would further promote the use of more environmentally friendly electricity generation options. Such a measure would also mean that renewable generation would be competitive at comparatively lower levels of carbon taxation.

From a policy perspective, the rather sobering conclusion is that carbon taxation, the most researched and technology neutral policy intervention, seems to have at best a minor impact on the optimal system configuration of microgrids, with its effects mostly being limited to increasing the total energy procurement cost for the microgrid. However, targeted interventions to boost adoption of one particular technology over the other are also effective, as proven by adoption of solar panels in the reviewed Greek settings. More heavy-handed interventions, such as obligatory emissions reductions are also proven to be effective in steering the system configuration of microgrids towards renewable energy sources, but this is accompanied by a large increase in private costs, casting doubt upon the feasibility of such measures.

The parameters on which microgrids are evaluated in the reviewed papers, are rather narrow: only the total or operational energy procurement costs and carbon emissions are considered. Lo Prete et al. [9] for instance show that the adoption of microgrids representing 8% of total generation capacity would lead to an increase of 30% in reliability of the entire electrical network. This shows that microgrids can certainly offer benefits where reliability is concerned. However, these benefits are neither valued nor investigated at the level of an individual microgrid by the reviewed papers, meaning the adoption of microgrid technology is possibly undervalued. This is clearly a promising avenue of further research.

Additionally, the impact of different tariffs systems is not investigated in the reviewed papers, especially considering that a restructuring of the current tariff system might incentivise some behaviour while penalising other behaviours. See for example Schreiber et al. [20] for a discussion on a capacity pricing model: the tariffs they design are not linked to the time of day when energy is required from the grid, but rather what the peak withdrawal power is. Their approach is exclusively focussed on the electricity component of energy demand, and takes a system view, choosing not to focus on the individual microgrid level. While therefore their work is outside the scope of this review paper, it is still relevant in that it shows that tariffs can be used to steer the behaviour of connected consumers in certain directions. Given this effect of tariffs, it stands to reason that a novel tariff system could have repercussions on the optimal design of microgrids; this is however an area that has not received any research attention up until now.

From a methodological point of view, we would like to recommend that future studies all include a baseline case, both with regards to the adoption of microgrid technologies and the proposed policy interventions. Where microgrid technologies are concerned, a baseline scenario would allow for a clear cost-benefit analysis to decide whether or not the adoption of a microgrid is economically viable. When it comes to policy analysis, the presence of a baseline scenario would greatly facilitate impact assessment of the considered policies, as it would enable “before and after” discussions.

Additionally, we would recommend that future studies report all relevant data used to produce the results, including not only equipment installation and maintenance costs, energy tariffs and taxation levels, but also information relating to the heat and power demand of the considered microgrid as well as the rated heat and power capacities of the selected technologies. Such disclosure would greatly help in allowing the reproduction of reported results, allow for the assessment of the impact of changes in technology costs or tariffs and even enable the investigation of parameters, such as microgrid size which have remained uninvestigated up until now.

6 CONCLUSION

In this paper, we have reviewed the current research literature concerning the impact of policy measures on the economically optimal configuration of microgrids. With regards to the first goal of this review paper, outlining the current state of the art in research surrounding the economics of microgrids, we have shown that the methodology of choice is the minimisation of operational or lifetime costs associated with the operation of the microgrid, depending on the time horizon. The used optimisation models in the literature are similar both in objective function and in decision variables. The current available literature on the impact of policy measures on the economically optimal configuration of microgrids considers microgrid sizes ranging from single buildings up to entire communities, but without explicitly controlling for the effects of microgrid size on the reported results. When it comes to the investigated policy measures in the literature, it is apparent that a lot of research attention has been devoted to the topics of carbon taxation and TOU-tariffs, with other subjects such as tax incentives or command and control policies only receiving moderate research attention. Furthermore, concerning the objective of outlining any research gaps, we have shown that the exploration of the impact of tariff systems other than TOU-pricing on the optimal configuration of a microgrid hasn't received research attention up until now, making this an interesting avenue for further research. Our most significant finding is that, where the most often viable reported system configuration is concerned, the current scientific consensus is that CHP-powered microgrids are the most economically viable type of microgrid under a wide range of policy interventions, with renewable powered microgrids only viable in fringe cases, making the often-heard claim that microgrids will allow for greater penetration of renewable sources highly suspect at best.

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