Multi-Criteria Decision Support Methods for Renewable Energy Systems on Islands

C. Wimmler, G. Hejazi, E. de Oliveira Fernandes, C. Moreira, and S. Connors

Abstract—**Islands often are confronted with severe energy challenges especially those far from the main land which operate as isolated energy systems. In those cases electricity, the queen of the energy vectors shall be obtained from diversified sources to alleviate the burden of the dependence on fossil fuels. Thereby, the generation of electricity from renewable energy sources in combination with electricity storage becomes an irrecusably challenge in the nearby future. Often a variety of criteria can be applied to identify the suitability of technologies, whereas no ideal family of criteria has been defined in the literature. Hence, decision support for energy planning and management is required. This paper reviews the state-of-the-art of multi-criteria decision support methods applied to renewable energy and storage technologies. It will be analyzed where the current focus is placed on. The gaps of those analyzed studies will be evaluated and key aspects for future energy planning considerations for islands will be proposed. Finally, an outlook for a newly developed concept for island energy planning will be presented. Indeed, for most isolated islands renewable energy technologies in combination with storage devices are a desirable and valued solution for sustainable development.**

Index Terms—**Island energy planning, multi-criteria decision support methods, renewable energy technologies, sustainable development.**

I. INTRODUCTION

Islands face diverse similarities in terms of their energy problems. Apart from their insularity and often not being grid-connected to the mainland energy network there are commonly social issues caused by not having sufficient energy, i.e. a high degree of young people unemployment that causes a trend of immigration, a lack of specialized work force, different levels of population density or a conservative mentality [1]. Plus, often welfare of islands depends on specific industries, mainly tourism, fishing and local businesses [2]. Even though tourism generates financial benefits, it is also the main driver for another problem; that of an increasing and highly season-depended energy and water demand [1], [3], [4]. Indeed, during the peak summer season many islands are confronted with energy security issues [5]. In correlation with tourism a high variation in the number of island inhabitants occurs [4], which during the main season might exceed that of the off-peak season by a few times [6].

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Considering that the energy demand will continue growing steadily in the next decades, precise energy planning and management as well as changing energy supply alternatives to more local ones can be a solution to overcome these issues [3].

Electricity represents the most flexible form of energy, as it can be used for heating, transportation and, of cause, as electricity. While fossil fuel imports are severely expensive and make an island dependent [7], the usage of locally available and abundant resources should be encouraged. In fact, most islands possess a diversity of resources, both on land and at sea. It is a matter of using these resources to foster sustainable development within an island energy system [3], [8], [9].

II. SUSTAINABILITY ASSESSMENT

Sustainability is certainly one of the major aspects for the realization of nearly any renewable energy project. Though, the indicators of a sustainability assessment need to be determined based on achieving a specific objective. As the solution should fulfill an islands energy requirements there are many real world factors that can be affected by the solution. Hence, it is essential to consider the criteria that can be relevant for renewable energy and storage technologies on islands. Since evaluating the consequences of the solution considering multi-criteria aspects is challenging, multi-criteria decision making (MCDM) methods can be applied to the energy planning problems. Such decision support is particularly valued by decision and policy makers.

Ness *et al.* [10] define *"The purpose of sustainability assessment is to provide decision-makers with an evaluation of global to local integrated nature–society systems in short and long term perspectives in order to assist them to determine which actions should or should not be taken in an attempt to make society sustainable"*.

A large variety of sustainable development indicators and sustainability assessment methodologies is presented in [11]. Thereby, an overall of 41 indices were identified and classified according to number of sub-indicators, scaling/normalization, weighting and aggregation. Besides efforts to measure sustainability as an integral approach, most cases only consider either environmental or economic or social aspects.

In the reviewed researches various sustainable indicators have been applied to renewable energy technologies (RETs) (Table II). The success of the assessment depends on the effectiveness of indicators for each criteria on that can correspond to a problem and/or fulfill the objective.

In [12] sustainability criteria (resource, environmental, economic and social) were used for technology selection. The

considered indicators were efficiency (%), installation cost (USD/kW), electricity cost (ct/kWh), CO_2 (kgCO_2/kWh) and area (km^2/kW).

Another approach which only considers techno-economic criteria for onshore and offshore wind, geothermal, small hydropower, solar and photovoltaic power was presented by [13]. While the technical indicators are construction period, technical lifetime, capacity factor and maximum availability, the economic indicators are investment cost, fixed and variable operations and maintenance cost as well as progress ratio. An even more comprehensive list of indicators is presented in [14], whereas the sustainability aspects are grouped in technical, economic, environmental and social criteria (see Table I).

TABLE I: SELECTION CRITERIA FOR SUSTAINABLE ENERGY PLANNING [14]

Criteria	Indicators
Technical	Efficiency, exergy efficiency, primary energy ratio, safety, reliability, maturity, others
Economic	Investment cost, operation and maintenance cost, fuel cost, electric cost, net present value, payback period, service life, equivalent annual cost, others
Environmental	NO_x emission, CO_2 emission, CO emission, SO_2 emission, particles emission, non-methane volatile organic compounds, land use, noise, others
Social	Social acceptability, job creation, social benefits, others

Because of the nature of the systems the selection process for storage technologies is also based on different criteria and indicators. Barin *et al.* divide in qualitative and quantitative characteristics to determine the storage energy technology in a power quality scenario [15]. Qualitative indicators focus on load management, technical maturity and power quality; with the respective characteristics being load leveling, load following, spinning reserve, back-up or typical usage.

A sustainability index approach was undertaken by [16]. By this means, a weighted sum approach was used to quantify each indicator according to its importance. Criteria ranged from economic and environmental aspects to risk, but also considered indicators such as reliability, system life or energy density ratio. The evaluation reviewed lead acid and lithium batteries as well as fuel cells, whereas fuel cells come top in the selection process. Further selection procedures that considered similar selection criteria and indicators as the above mentioned researches are presented in [17]-[19].

This section of the paper clearly demonstrated that there are some common criteria and indicators. Though, it is essential to select an appropriate set of criteria based on the objective of the planning. The whole assessment should be considered as integrated process rather than a solitaire one. Plus, most indicators used for island cases are actually based on cases from the mainland. Therefore, it is necessary to consider criteria that specifically correspond to islands.

III. MULTI-CRITERIA DECISION MAKING METHODS FOR RENEWABLE ENERGY SYSTEMS

MCDM can be an alternative to support decision and policy makers in their decision process. Depending on the values and preferences of a decision maker, different approaches can be attained. The selection process of an appropriate MCDM method for renewable energy planning is discussed in [20]. According to [21] the aims of MCDM are:
- *"to aid decision-makers to be consistent with fixed 'general' objectives;*
- *to use representative data and transparent assessment procedures; and*
- *to help the accomplishment of decisional processes, focusing on increasing its efficiency."*

A very comprehensive review of MCDM methods was undertaken by [22]. The analyzed methods include weighted sum/product method, analytical hierarchy process (AHP), preference ranking organization method for enrichment evaluation (PROMETHEE), elimination and choice translating reality (ELECTRE), technique for order preference by similarity to ideal solutions (TOPSIS), compromise programming (CP) and multi-attribute utility theory (MAUT). Additionally, Wang *et al.* [14] present fuzzy set methodology, grey relational method and others (i.e. Preference assessment by imprecise ratio statements (PARIS)) as MCDM methods for sustainable energy decision making. Besides, an integrated approach considering MCDM methods along with Geographic Information System (GIS) tools has been established by [23]. Indeed, combinations of GIS and MCDM are used for site selection of technologies; i.e. wind [24], solar [25] or tidal stream [26].

It should be noted that the main focus of this paper is not to analyze each method, its strengths and weaknesses, rather than to highlight the multitude of methods available. In the end, the method should be capable of incorporating different decision maker ś preferences and data availability.

IV. MCDM METHODS, CRITERIA AND INDICATORS FOR SUSTAINABLE ENERGY PLANNING

Extensive research in the permanent literature has been undertaken to assess the current state-of-the-art of applied and conceptual research in the area of MCDM for renewable energy and storage systems. Therefore, the purpose, criteria, indicators and MCDM method for each research were analyzed. Plus, the data type of criteria (quantitative, qualitative or mixed) and an evaluation if offshore and storage technologies were included in these cases were studied (see Table II). Additionally, Table III summarizes the applied system size and location as well as the considered technologies.

TABLE II: EVALUATION OF MULTI-CRITERIA DECISION MAKING METHODS APPLIED TO RENEWABLE ENERGY AND STORAGE TECHNOLOGIES

Purpose/target	Criteria and Indicators	Offshore	Storage	# indicator&Data type	Multi-criteria decision making method*
Category: Impact assessment					
Hong *et al.* [27] — Impact of rural electrification using RET to improve energy access	**T – Ec**: cost, life, power consumed, alternatives consumed **S – Ec**: education level, occupation	N	N	6 M	Multiple correspondence analysis

TABLE II continued

Silva *et al.* [28]	Assessment of rural electrification with renewable energy systems	**Ec**: electricity generation cost **S**: employment generation **En**: land use, avoided CO$_2$ emissions	N	N	4 QL	Multi-objective decision making – goal programming
Cherni *et al.* [29]	Calculate set of appropriate energy options to fulfill local needs	Physical, Financial, Natural, Social, Human	N	N	5 QL	SURE tool
Heo *et al.* [30]	Establish criteria for renewable energy dissemination programs	**T**: Superiority of technology, Completeness of technology, Reliability of technology and operation, Possibility of acquiring original technology **Market**: Domestic market size and competitiveness, Global market size and competitiveness, Competitive power of domestic technology **Ec**: Supply capability, Economic feasibility, Supply durability **En**: Reduction of greenhouse gas and pollutants, Requirement of resources, Acceptability of local residents **Policy**: Contribution to achieve dissemination goal, Spillover effect, Linkage with R&D program, Influence of existing social system	N	N	17 QL	Fuzzy AHP
Chatzi-mouratidis *et al* [31]	Evaluate impact on the living standard of local communities	**Quality of life**: accident fatalities, non-radioactive emissions, radioactivity, land requirement **S – Ec**: job creation, compensation rates, social acceptance	N	N	7 M	AHP
Heano, *et al* [32]	Selecting energy generation systems for improvement of rural livelihoods	Physical, Financial, Natural, Social, Human	N	N	5 QL	SURE tool
Category: Power generation optimization						
Stein [33]	Rank various renewable and non-renewable electricity generation technologies	**Ec**: total overnight cost, variable O&M, fixed O&M, fuel cost; **T**: Production efficiency, capacity factor **En**: External costs, loss of life expectancy **S**: fuel reserve years, job creation, net import as % of consumption	N	N	11 QN	AHP
Ribeiro *et al.* [34]	Support the evaluation of different electricity generation scenarios	**T**: national industry, energy dependency, diversity of mix, rate of dispatchable power **Ec**: costs, investment in transmission network **En**: visual impact, CO$_2$ emissions, land use **S**: employment, local income, public health, noise	N	N	13 M	Value measurement method; includes impact evaluation, direct weighting and trade-off analysis
Begic *et al.* [35]	Multi-criteria sustainability assessment of various options of the energy power system	**Resource**: fuel, carbon steel, stainless steel, copper, aluminum, insulation **En**: CO$_2$, SO$_2$, NO$_x$ **Ec**: Energy cost, investment, efficiency **S**: job, diversity	N	N	14 QN	Analysis and synthesis of indexes under deficiency of information (ASPID)
Suo *et al.* [36]	Select optimal alternative according to their optimism degrees	**T**: energy intensity, retirement, current capacity, potential capacity, service life **Ec**: O&M cost, capital cost **En**: GHG intensity	N	N	8 QN	advanced ordered weighted averaging (AOWA)
Papadopoulos *et al.* [37]	Optimization of decentralized/ isolated energy systems	**Ec**: NPV, life cycle cost, depreciated payback period, black-out cost **En**: CO$_2$	N	N	5 QN	ELECTRE III
La Rovere *et al.* [38]	Analyze the sustainability of the expansion of electricity generation	**T**: Net generation efficiency, average annual availability, construction period, electrical generation potential **Ec**: specific investment, cost-benefit index, percentage of imported inputs **En**: water consumption, specific CO$_2$ emissions, occupied area, percentage effective land use, specific emissions of non-CO$_2$ gas emissions **S**: number of direct jobs created, average job income level, job seasonality	N	N	15 M	Data envelope analysis (DEA)
Terrados *et al.* [39]	Contribute to renewable energies development at regional level	**T**: total primary energy saved, maturity of technology, technical know-how of local actors, continuity and predictability of resources **En**: CO$_2$, other emissions (SO$_2$, NO$_x$), other impacts (noise, visual impact, landscape) **S – Ec**: job creation, financial requirements, compatibility with local, regional and national policies	N	N	11 QN	PROMETHEE
Chatzimou-ratidis *et al.* [40]	Evaluation of types of power plant	**T – sustainability**: efficiency coefficient, availability, capacity, reserves/ production (R/P) ratio **Ec**: capital cost, fixed O&M cost, variable O&M cost, fuel cost, external cost	N	N	8 QN	AHP
Van Alphen *et al.* [41]	Quantification and evaluation of the potentials of available PV and wind	**T**: excess electricity, renewable energy faction **Ec**: capital cost, annual cost, NPV, Levelized cost of energy **En**: emission reduction **S**: fossil fuel savings	N	N	8 QN	Weighted sum (DEFINITE software)

TABLE II continued

Category: Policy selection						
Kahraman *et al.* [42]	Select the best energy policy alternative	**T**: feasibility, risk, reliability, duration of preparation phase, duration of implementation phase, continuity and predictability of performance, local technical know how **En**: pollutant emissions, land requirements, need of waste disposal **Ec**: implementation cost, availability of funds, economic value (IRR, cost/benefit) **S**: compatibility with national energy policy objectives, political acceptance, social acceptance, labor impact	N	N	16 QL	Fuzzy AHP
Yi *et al.* [43]	Solutions to overcome North Koreas chronic energy shortage	**Ec**: facility construction cost, facility maintenance cost, related infrastructure construction cost **Benefit** [S]: availability of energy source within North Korea, area development of North Korea, improvement of inter-Korean relations, development of related industry in South Korea **Risk** [T]: technology transfer problem, appropriateness to North Korea, technological availability and readiness in South Korea	N	N	10 QL	AHP
Blechinger, *et al.* [44]	Ascertain preferences for policy measures and instruments	**En**: direct contribution to GHG mitigation, indirect environmental effect **Political acceptability**: cost efficiency, dynamic cost, competiveness, equity, flexibility, stringency for non-compliance **Feasibility of implementation**: implementation network capacity, administrative feasibility, financial feasibility	N	N	10 QL	AHP and Simple Multi-Attribute Rating Technique (SMART)
Category: Scenario evaluation						
Diakoulaki *et al.* [45]	Examine scenarios for the expansion of electricity system	**T**: guaranteed energy, available power during peak load, security of supply **Ec**: investment cost, production cost **En**: CO_2 increase, SO_2, NO_x	N	N	8 M	PROMETHEE
Georgopoulou *et al.* [46]	Choose among alternative energy policies at regional level	**T**: safety in covering peak load demand, operationality, stability of the network **Ec**: investment cost, O&M cost **Political**: cohesion to local economic activities, regional employment **En**: air quality, noise, visual amenity, depletion of finite energy sources, risk of climate change, ecosystem ś protection, land use, implementation of EU and national environmental policy	N	N	15 M	ELECTRE III
Category: Technology Selection						
Afgan *et al.* [12]	Define energy indicators used in the assessment of energy systems which meet sustainability criterion	**Resource**: Efficiency **En**: Installation cost, electricity cost **Ec**: CO_2 emissions **S**: Area	Y	N	5 QN	Weighted arithmetic mean
Baysal *et al.* [13]	Selection of renewable energy power plant technologies	**T**: construction period, technical lifetime, capacity factor, maximum availability **Ec:** investment cost, fixed and variable O&M cost, progress ratio	Y	N	7 QL	Fizzy data envelopment analysis (FDEA)
Beccali *et al.* [21]	Diffusion of renewable energy technologies at regional scale	**T**: Targets of primary energy saving in regional scale, Technical maturity & reliability, Consistence of installation and maintenance requirements with local technical know-how, Continuity and predictability of performances, Cost of saved primary energy **Energy and En**: Sustainability according to greenhouse pollutant emissions, Sustainability according to other pollutant emissions, Land requirement, Sustainability according to other environmental impacts **S – Ec**: Labor impact, Market maturity, Compatibility with political, legislative and administrative situation	N	N	13 M	ELECTRE
Tsoutsos *et al.* [47]	Multi-criteria methodology for sustainable energy planning on the island of Crete	**T – Ec**: Investment, O&M cost, conventional fuel savings, maturity of technology, safety of supply **S – En**: CO_2 emissions avoided, contribution to local development and welfare, social acceptance and viability of the remaining environmental effects	N	N	8 M	PROMETHEE
Burton *et al.* [48]	Comparison of small scale schemes with large-scale alternatives	**T**: generation capacity, lifespan **Ec**: capital cost, O&M cost **En**: CO_2, impact upon natural environment **S**: noise, social effects	N	N	8 M	MACBETH
Cavallaro *et al.* [49]	Feasibility assessment to install wind turbines	**T – Ec**: investment cost, O&M cost, energy production capacity, savings of finite energy sources, maturity of technology, realization time **En**: CO_2 emissions avoided, visual impact, acoustic noise, impact on eco-system, social acceptability	N	N	11 M	NAIADE

TABLE II continued						
Afgan *et al.* [50]	Assessment of hydrogen energy options in comparison with renewables	**Performance**: Efficiency, electricity cost, capital cost, life time **Market**: European market, world market **En**: CO_2, NO_x, Kyoto indicator **S**: area, new jobs	N	Y	11 QN	Weighted arithmetic mean
Afgan *et al.* [51]	Evaluation of hybrid energy systems	**Ec**: Efficiency, electricity cost, investment cost **En**: CO_2 emissions **S**: NO_x emissions	N	Y	5 QN	Weighted arithmetic mean of indicators
Mourmouris *et al.* [52]	Support energy planning for promoting the use of RETs	**T**: efficiency, safety, availability, **En**: environmental quality, visual impacts, impacts on flora and fauna, CO_2, SO_2, NO_x emissions **Ec**: economic benefits for the region, creation of development **S**: employment in the energy sector, land used, social acceptability	N	N	14 M	REGIME
Topcu *et al.* [53]	Selection of suitable electricity generation alternatives	**P**: sustainability of the energy resource, suitability of potential site **En**: Externality cost **Ec**: Levelized cost **Political and uncontrollable**: stability	N	N	5 M	PROMETHEE
Kaldellis *et al.* [54]	Provide decision makers with tool to evaluate technologies to support power generation	**T**: system efficiency, capacity factor, fuel availability, existing experience **Ec**: 14 criteria, i.e. high paid cost/tn of CO_2, fuel cost, construction cost/long payback period, etc. **En**: 14 criteria, i.e. high gaseous and particulate emissions, hot waste water disposal, microclimate change, etc. **S**: 9 criteria, i.e. noise, accidents, health hazards, people relocation etc.	N	N	41 QL	Delphi method (qualitative evaluating approach)
Kaya *et al.* [55]	1) determining best renewable energy alternative 2) selecting site location	**T**: technical efficiency, exergy efficiency **Ec**: Investment cost, O&M **En**: NO_x emissions, CO_2 emissions, land use **S**: social acceptability, job creation	N	N	9 QL	integrated fuzzy VIKOR-AHP algorithm
Evans *et al.* [56]	Assessment of RETs using sustainability indicators	**T**: Availability and limitations, efficiency **Ec**: Price **En**: CO_2 emissions, land use, water consumption **S**: social impacts	N	N	7 QL	Equal weights
Onat *et al.* [57]	Assessment of electricity generating technologies	**T**: Availability, efficiency **Ec**: Unit energy cost **En**: CO_2 emissions, land use, fresh water consumption **S**: external costs, external benefits	N	N	8 M	Ranking of criteria and equal weights
Varun *et al.* [58]	Technology selection for sustainable development	**T**: power rating, life **Ec**: energy pay-back time, cost of electricity generation **En**: GHG emissions	N	N	5 QN	Figure of merit based on equal weighting
Cavallaro[59]	Preliminary assessment of CSP technologies	**T**: maturity of technology, temperature, solar capacity factor **Ec**: investment cost, O&M cost, LEC **En**: environmental impact	N	N	7 M	PROMETHEE, GAIA
Buchholz *et al.* [60]	Assess sustainability of bioenergy systems with focus on multi-stakeholder inclusion	**Ecological**: reduced competition for fertile land **Ec**: increased local commerce, high cost efficiency, high supply security **S**: low training needs, high employment rate, diversity and certainty in ownership and business schemes, low planning and monitoring needs	N	N	8 QL	AHP, MAUT, PROMETHEE and NAIADE
Pilavachi *et al.* [61]	Evaluate electrical energy generation options	**T**: efficiency, service of life **En**: CO_2 emissions, NO_x emissions **Ec**: capital cost, O&M costs, electricity cost	N	N	7 QN	AHP
Erol *et al.* [62]	Facilitate energy resource planning activities	**T**: possibility of acquiring original technology, superiority of technology, completeness of technology **Ec**: reliability of technology and operation, ease of access to the source, additional investment, source durability, supplementary usage of resources **En**: effect of the technology to the environment, carbon footprint, requirement of resources **Public**: acceptability by local resident	N	N	12 QL	AHP
Nigim *et al.* [63]	Assist communities in prioritizing their RES alternatives	Ecological impact, social and economic benefits, educational potential, Resource availability, technical feasibility, financial feasibility	N	N	6 QL	AHP and SIMUS tool
Streimikiene *et al.* [64]	Choosing the most sustainable electricity generation technologies	**Ec**: private costs, average availability (load) factor, security of supply, costs of grid connection, peal load response **En**: GHG emissions, environmental external costs, radionuclide external cost, human health impact **S**: technology-specific job opportunities, food safety risk, fatal accidents from the past experience, severe accidents perceived in future	N	N	13 M	Multimoora and TOPSIS
San Cristobal [65]	Selection of a Renewable Energy investment project	**T**: power, operating hours, implementation period, useful life **Ec**: investment ratio, O&M costs **En**: tons of CO_2 avoided	N	N	7 QN	Compromise ranking method VIKOR

TABLE II continued

Category: Site selection							
Al-Yahyai *et al.* [24]	Derive wind farm land suitability index and classification	**T**: wind power density, energy demand matching, percentage of sustainable wind, turbulence intensity, sand dunes **Ec**: distance to road, terrain slope **En**: historical locations, wildlife and natural reserves **S**: urban area	N	N	10	M	AHP with Ordered Weigh Averaging
Charabi *et al.* [25]	Assess the land suitability for large PV farms implementation	**T**: solar radiation, land accessibility, land use **Ec**: grid proximity, land slope, load poles **En**: sensitive areas, hydrographic line, sand/dusk risk	N	N	9	M	Fuzzy Logic Ordered Weighted Averaging (FLOWA)
Defne *et al.* [26]	Assist in selecting most suitable locations for tidal stream projects	**Physical**: power density **En**: environmental score **S – Ec**: accessibility	Y	N	3	M	GIS and equal weighting
Haurant *et al.* [66]	Selection of photovoltaic plant projects	**T**: net production **Geoeconomic**: rent area unoccupied by the installation **Ecological**: study of the potential ecological degradation in the files **En**: relevance of visual impact presentation in the files, observer-plant minimum distance **Territorial use**: use conflicts risks **Ec**: economic activity and inhabitants ´financial benefits related to RES facilities, financial incomes at the communal level	N	N	8	M	ELECTRE
Zhang *et al.* [67]	Selecting a sustainable energy plan for Nanjing city	**T**: efficiency, safety, reliability **Ec**: investment cost, O&M cost **En**: GHG emissions reduction, land use **S**: job creation, social benefit	N	N	8	QL	Fuzzy integral method
Category: Storage technology selection							
Barin *et al.* [15]	Evaluate operation of storage energy systems	**T**: efficiency, load management, technical maturity, lifecycle, power quality **Ec**: costs	N	Y	6	M	AHP and fuzzy sets
Raza *et al.* [16]	Compare different energy storage systems for their sustainability	**T**: fast load response capability, reliability, system life, efficiency, capacity or efficiency variation, risk factor, modularity production, energy density ratio **En**: cost **Ec**: environmental impact	N	Y	10	M	Sustainable Index approach using weighted sum

Abbreviations: N = No; Y = Yes; T = Technical; En = Environmental; Ec = Economic; S = Social; I = Institutional; P = Physical; T – Ec = Techno-economic; S – Ec = Socio-economic; S – En = Socio-environmental
NPV = Net Present Value; O&M = Operation and Maintenance; PP = Payback period; CSP = Concentrated solar power; LEC = Levelized electricity cost
Data type can be quantitative (QN), qualitative (QL) or mixed (M)
*The different MCDM methods are not further explained within this paper. Precise information about each method can be found under the respective references.

The review of MCDM for renewable energy and storage systems highlights:

- Most research is undertaken for technology selections and power system optimization;
- Offshore and storage technologies lack consideration;
- Combinations of offshore RET and storage technologies could not be found
- Criteria vary, but the most common are: technical, environmental, economic and social
- The chosen indicators also diverge strongly (the most common by criteria are; technical: efficiency, availability and lifetime; economic: investment cost and O&M cost; environmental: CO_2 emissions and land use; social: job creation, acceptability);
- The majority of researches uses mixed data sets with an average set of 8-10 indicators;
- AHP is the most frequently applied method in the analyzed researches

When it comes to the applicability of reviewed studies (Table III), immediately the high focus on PV (>75%) and wind (>70%) becomes evident. Moreover, biomass, hydro and non-renewables are assessed in around 50% of the researches. Hydrogen and offshore technologies only play a marginal role. In terms of system size various studies focus on island energy systems, but with a limited number of technologies considered. Moreover, it is essential to highlight that none of the studies focused on all technologies. Indeed, out of 47 studies reviewed only twice offshore technologies were considered.

V. DISCUSSION ON FUTURE ENERGY PLANNING CONSIDERATIONS FOR ISLANDS

Owing to its particular, often natural, conditions, isolated islands require a more acquainted usage of renewable resources. Case specific energy planning and management is highly advisable, because each island can be considered as an individual and differing energy system.

The following conductions will reflect upon such a system and point out important aspects to be considered for island energy planning. Regarding the system size, small not grid-connected islands ranging from a few thousand up to a million inhabitants shall be accounted for.

A. Future Development and Energy Time Shift

While an islands energy demand often fluctuates by a few folds within a year, long-term planning considers time horizons of 25 years and more. In this time frame noticeable changes can occur within an island energy system; either increasing or decreasing. Consequently, forecasts are vital to define the compulsory future energy requirements. Such investigation should also consider by how much energy efficiency can decrease consumption and by how much

demand changes due to an increase or decrease of habitants.

Besides, it should be a major interest to assess the possibilities of energy management. On the one hand side, typical demand side measures are peak clipping, valley lifting, load shifting, strategic conversation, strategic load growth or a flexible load shape. Indeed, high flexibility in the load shape is essential to cope with variable renewables. On the other side, supply side management is desirable. Thereby, the focus is placed on efficiency along the whole value chain, ranging from generation to distribution and the final customer. Smart technology and smart grids are the connection between demand and supply and therefore possess a major role within the planning and secure energy supply.

TABLE III: EVALUATION OF SYSTEM SIZE AND TECHNOLOGY

Ref.	Applied system size and location (Comment)	Onshore						Offshore			Fossil fuels
		S	W	HY	B	G	HG	W	WA	T	
[12]	Any – conceptual method	✓	✓	✓	✓	✓	✓				✓
[13]	Technology specific selection	✓	✓	✓		✓		✓			
[21]	Regional, island of Sardinia, Italy	✓	✓	✓	✓						✓
[24]	Local, regional, national, Oman		✓								
[25]	Local, regional, national, Oman	✓									
[26]	Local, regional, coast of Georgia									✓	
[27]	Off-grid, rural, Pangan-an Island, Philippines	✓									
[28]	Remote areas, rural, non-interconnected zones Columbia	✓	✓	✓	✓						✓
[29]	Rural livelihoods, communities, San Jose, Colombia	✓		✓	✓						✓
[30]	National, Korea										
[31]	Local community level up to national level	✓	✓	✓	✓	✓					✓
[32]	Rural livelihoods, communities, Jambaló, Colombia	✓		✓	✓						✓
[33]	Any - Power system optimization model	✓	✓	✓	✓	✓					✓
[34]	Large, national, Portugal		✓	✓							✓
[35]	Regional to national - Bosnia	✓	✓	✓	✓						✓
[36]	Local, regional, power stations		✓	✓	✓						✓
[37]	Remote region, isolated Greek islands Karpathos and Kassos	✓	✓		✓						
[38]	Any – conceptual method		✓	✓	✓						
[39]	Local, regional, Province Jaen, Spain	✓	✓	✓	✓						✓
[40]	Local, regional to national	✓	✓	✓	✓	✓					✓
[41]	Local, regional, city, islands, Male, Maldives	✓	✓								
[42]	National, Turkey	✓	✓	✓	✓	✓					
[43]	National, North Korea	✓	✓	✓	✓	✓					✓
[44]	Regional, national policies, Trinidad and Tobago										
[45]	National, Greece		✓	✓							✓
[46]	Local, regional level, Crete	✓	✓		✓						✓
[47]	Regional, Crete	✓	✓		✓						
[48]	Local, small scale, Borough of Kirklees in Yorkshire, UK	✓	✓	✓	✓						✓
[49]	Local to regional, island of Salina, Italy		✓								
[50]	Any – conceptual method	✓	✓				✓				✓
[51]	Any – conceptual method	✓	✓		✓		✓				✓
[52]	Regional, Thassos, Greece	✓	✓	✓	✓	✓					
[53]	Regional to national, Turkey	✓	✓	✓	✓						✓
[54]	Regional and National, Crete and Greece	✓	✓								✓
[55]	Local, city, Istanbul	✓	✓	✓	✓	✓					
[56]	Any – conceptual method	✓	✓	✓		✓					
[57]	Any – conceptual method	✓	✓	✓		✓	✓				✓
[58]	International/National	✓	✓	✓							
[59]	Technology specific selection	✓									
[60]	Local, regional, national, Uganda				✓						✓
[61]	Technology specific selection						✓				✓
[62]	Local, regional, district of Aydin, Turkey	✓	✓	✓		✓					✓
[63]	Local, communities, Waterloo Region, southern Ontario	✓	✓	✓		✓					
[64]	Technology specific selection	✓	✓	✓	✓						✓
[65]	Local, regional, national	✓	✓	✓	✓						
[66]	Local, regional, Corsica Island	✓									
[67]	Local, city-level, Nanjing, China	✓			✓	✓					
Total (47)		**36**	**34**	**28**	**26**	**14**	**5**	**1**	**0**	**1**	**24**
S = Solar; W = Wind; HY = Hydro; HG = Hydrogen; G = Geothermal; B = Biomass; WA = Wave; T = Tidal; [✓] = yes											

B. Future Development and Energy Vector Shift

In addition to the changes resulting from energy efficiency and time shifts, the effects of energy vector shifts should be assessed. This is particularly important for small island energy systems. There, large scale heat generation from RETs is impractical. Even with combined heat and power systems large heat sinks might be required during off-peak season. This consideration is vital for decision makers, when planning for a system that is mainly driven by renewable based electricity. Indeed, within 25-50 years' time it could be a possible scenario to have the bulk of an islands car fleet powered by electricity. Plus, currently fossil fuel driven heating appliances might be electricity driven by then. Certainly, it is not the intension to replace all heat and transport fuel requirements with electricity. Especially, for the building and industry sector different alternatives of heat generation from renewables are worth considering; i.e. solar thermal, biomass, ground source heat pumps, etc.

Due to the vector shift, and despite the energy savings from energy efficiency and management, the overall electricity demand on an island might increase remarkably within the considered time horizon. Hence, the new energy paradigm will create a new load profile.

Thereby, it should be aimed for a flexible load shape, whereas demand in the form of the inhabitant's requirements can match with the energy provided from renewables. Additionally, storage capacity will be required. This can either be storage plants or batteries, but also fossil fuel powered back-up generators. Nonetheless, with fossil fuel back-up the dependency on fossil fuel imports remains. Consequently, the planning should evaluate some type of storage technology or capacity. Due to the small system size the focus is not places on fast responding back-up capacity for system stabilization, but also long-term back-up when there are longer periods without or limited availability of RET based power. In order to reduce the unavailability of a large share of RET, technology diversification is highly encouraged.

C. Enlarge Number of Technologies within Selection Process

Choosing the right technology is one of the most important tasks for decision makers when undergoing energy planning for sustainable development. While in the past decades the number of possible REt alternatives was rather small, and technologies could be selected mainly from a commercial point of view, by now, several market commercial concepts are available. Many of them are highly competitive with one another. For that reason more precise targets need to be defined before selecting a technology. Emerging concepts, mainly offshore technologies, should not be neglected in the selection process. Especially in spatially limited islands, but also ones that contain heritage and natural habitats, a focus on offshore rather than onshore RETs is advisable.

Besides, islands do not necessarily seek for the most economic supply alternative, rather than for one that is sustainable. Aspects such as reducing import dependency and thus having energy security are often much higher valued.

Indeed, offshore RETs lack of market competitiveness yet, apart from offshore wind. Hence, the expectations and trends are promising. Offshore resources bear several advantages compared to their onshore counterparts, whereas especially environmental and social aspects could favor offshore technologies.

It is this variety of technologies that confronts decision makers with major challenges; 1) what technology or technology portfolio is most suitable one to cover the energy requirements?, and 2) how to combine RET and storage technologies to have a reliable and secure energy system? For that reason decision support methods are helpful to select appropriate technologies according to the preferences and local requirements of the specific case. Though, such methods should be able to incorporate the preferences of decision makers and allow for a differentiation of available data

D. New Island Energy Planning Concept

The discussion has highlighted the need for a holistic approach under the new energy paradigm. Electricity as a dominating energy vector can certainly supply the vast majority of an islands energy requirement with locally abundant resources. Therefore, more precise decision support is required. Diesel generators should only be considered an alternative once the storage system is not able to provide adequate back-up power.

A new concept, based on the conductions of the previous paragraphs is currently under development at the University of Porto. It is intended to develop a method whereby multiple MCDM processes will be undergone to propose a technology portfolio that can cover an islands energy requirements based on a combination of supply alternatives from renewable energy sources. At the present stage the concept is divided in 5 major phases.

1) Define demand and load profiles

The principal step is to define the current energy demand. Therefore, the peak capacity, annual demand and daily load profiles will be aimed for. As the future demand is subject to a variety of external factors, 9 different scenarios will be built to represent the future demand. Those scenarios are the combinations of three alternatives (conservative increase, progressive increase and very progressive increase) stating the amount of electricity to be covered from renewables along with three time frames (10 years, 20 years and 30 years).

- The conservative approach intends to fulfill the future (additional) electricity demand and whatever results from the phase-out of fossil fuel power plants.
- The progressive approach foresees replacing all fossil fuel power generation.
- Within the very progressive approach all fossil fuel power generation plus all heating and transportation services that can become electric within the specific time horizon shall be covered by renewable energy technologies.

Hence, for each of these 9 scenarios daily load profiles are required, depicting the hourly loads over the year. As precise measurements for everyday are often difficult to access and scarce, the profiles for weekday, Saturday and Sunday over the different months or seasons shall be used. A minimum of 3 load profiles is desired to perform the time series simulation in phase 4.

The following assumptions were reflected when compiling the scenarios.

- In all scenarios implying the conservative approach there is enough fossil fuel back-up available to integrate RET.
- For all scenarios implying the progressive approach a replacement of all fossil fuel generation by RETs can be done within the proposed time frames.
- The load profiles for all scenarios comprising the conservative or progressive approach are identical and will not change over time.
- All scenarios including the progressive or very progressive approach consider the usage of storage technologies. Suitable amounts of storage will be defined within phase 4. In order to guarantee 100% system reliability a minimum amount of fossil fuel back-up power might be required.
- Scenarios comprising the very progressive approach consider different amounts of energy vector shifts to be undertaken over time. Thereby, aproportionally increasing shifting potential will be considered over the time horizons.
- Different load profiles reflecting the service shifts will be applied in the scenarios comprising the very progressive approach.

2) Technology options

This step intends to evaluate different RETs according to the local resource availability and characteristics. In fact, 36 different onshore and offshore technologies will be assessed. Several emerging concepts, especially wave and tidal, can be added once more precise data is available. While the resource conditions assess the general suitability of the technology, with different technology specific characteristics, the number of possible technologies will be reduced and specified. The evaluation criteria are very technology specific and therefore allow for a more precise technology selection. For instance, within offshore wind there are floating and fixed devices, but due to the water depth around an island only floating devices might be suitable. Plus, within the floating devices various considerations regarding the mooring dynamics, hydrodynamics, aerodynamics and so forth are applied. For onshore technologies the criteria are more related to space limitation, shading or land accessibility.

In a similar manner criteria for each technology category have been defined to detect the most appropriate technology choice within each technology category. This primer multi-criteria approach has been chosen to minimize the amount of technologies to be considered for further evaluation.

3) Sustainability assessment

The sustainability assessment will be undertaken for all pre-specified technology choices over the three time horizons (10, 20 and 30 years). A family of criteria will be defined to evaluate the value and the consequences of the technologies under technical, economic, environmental and social aspects. Therefore, a MCDM process will be undertaken. Equal weighting is proposed in the first instance. Thereby, all pre-specified technologies will be ranked. Learning curves over the time horizons will be associated to each evaluation indicator; i.e. efficiency improvements, cost reduction, local perception, etc.

In a second approach each of the evaluation indicators can be graded by preferences and priorities; for instance by decision makers or energy agencies. This will give applicants of this concept a higher flexibility in their decision making process.

Once all technologies are ranked accordingly, only the top 5 technologies in each time horizon will be considered for further evaluation. Though, it will be a constraint to not use different technology choices with the same resource. The diversity of technologies is desired as the amount of storage can be reduced and the system becomes more reliable.

4) Determination of energy mix

At this stage the technologies and their natural resource availability are identified. The latter can be obtained from local weather stations. Additionally, the primarily collected load profiles for each scenario are available. Based on a time-series approach that considers the availability of each resource for each hour of the year along with the demand profile that defines the load for each hour of the year it is intended to define the energy mix that minimizes the maximum amount of RET and storage to be required. As a result, the energy mix for each of the 9 scenarios could consider up to 5 different technologies. At the current stage only one storage technology will be considered to cover the required back-up power. Though, it will be a further step to make use of multiple storage devices that can respond to the required services; some being used for grid stability and others for long-term energy storage.

Within this approach further technical parameters such as system availability, reliability and losses shall also be considered. The aspects of time constraints or network capacity can be for further research. In case no adequate back-up power from storage technologies is available a reversion to fossil fuel generators is considered. By using probability curves the time-series will be run multiple times so that an accurate system can be defined.

5) System analyses

The final step performs a comparison of the energy mix of each scenario considering its additional storage. Therefore, three evaluation indicators will be considered that allow for the selection of the most appropriate scenario and energy mix for an island energy system. The three indicators are levelized cost of the overall system including the storage system, annual CO_2 emissions saved and number of jobs created. Using preferences of the decision maker the most appropriate overall scenario can be determined.

Having used these compound MCDM procedures decision makers have the possibility to select the most appropriate technology mix from a very large number of technology choices. Moreover, the comparison between scenarios considering different time frames and amounts of power to be covered from RET, allows for a better understanding in defining long-term strategies for sustainable development.

VI. CONCLUSION

Even though some of the reviewed multi-criteria decision making methods were applied in the context of islands, the amount of technologies and aspects considered was limited. Indeed, the main objectives were technology selection, site location and power optimization rather than planning for a holistic sustainable future. New concepts, including energy

time and vector shift, are essential for island energy planning. Besides, sustainable development calls for a reduction of fossil fuels and import dependency, for which reason the usage of local abundant resources is highly encouraged. A new concept implying multiple MCDM processes to select from a vast number of technologies has be introduced.

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Pollution Control