Resource Efficient Applications through Design and Optimization of High Performance Heat Pump Based Hybrid Renewable Energy Systems in Ireland's Cool Marine Climate

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Abstract

Concern about security of energy supply, sustainability and climate change continues to motivate resource conscious communities to embrace energy efficiency and renewable energy. Although this transition is accelerating, many economic and technical challenges remain. This paper presents an overview of a proposed methodology, called HP-HRES-IRL, to design and optimize hybrid renewable energy system. The development of thermal hybrid energy systems that combine two or more renewable sources have the potential to provide higher and more cost effective renewable energy fractions when the appropriate size and combination of systems are utilized. HP-HRES-IRL methodology employs artificial intelligence tools for resource and climate data analysis in order to design and optimize systems that deliver low grade thermal energy in Ireland's cool marine climate. The methodology uses measured weather and thermal energy consumption data from both a public building and an industrial process over two years (2008 and 2009). Results prove the significant capital cost reductions with multi-source and show confidence in the use of the methodology and its capability to outline the most capital cost effective roadmap for a transition towards 100% renewable energy systems.

1. Introduction

Tackling climate change and ensuring security of energy supply while strengthening competitiveness are at the core of the European climate and energy strategy [1], [2], [3], [4]. The first step of the challenge to transform Europe into a highly energy-efficient, low carbon economy was taken by setting the "20-20-20 targets" that are to be met by 2020 [4]. Achieving the 20% targets (i.e. in 2020 20% lower greenhouse gas emissions than 1990, 20% of energy consumption from renewable sources and a 20% reduction in primary energy use compared with projected levels by improving energy efficiency) requires legislation be put in place as specified in the European "climate and energy package" which became law in 2009 [5]. The package drives energy efficiency which is addressed by the EU's energy efficiency action plan. The package also sets binding national targets for renewable energy which

collectively will lift the average renewable share across the EU to 20% by 2020, more than double the 2006 level of 9.2%. The national targets range from a renewables share of 10% in Malta to 16% in Ireland or 49% in Sweden. The Irish National Renewable Action Plan (NREAP) specifies that the 16% target is to be achieved by 40% renewable electricity, 12% renewable heat and 10% renewable transport.

Thermal applications account for approximately 55% of the final energy used worldwide; low temperature heat which is required for cooking, water and space heating and drying represents 82%; and high temperature heat for industrial processes is 18% [6]. Thermal applications are also estimated to consume the greatest proportion of energy delivered to European consumers [7] and 40% of the final energy used in Ireland [8]. Based on recent statistics, the share of renewable heating and cooling is approximately 4.4% in Ireland [9] and 12% in Europe, but it is envisaged to reach 100% by 2060 in some de-carbonizing heating scenarios [7]. The adoption of this energy scenario will require the use of the full potential of renewable energy sources to satisfy the heating and cooling demand.

Alongside binding legislation, in order to support its climate and energy strategy, EU also launched a Strategic Energy Technology Plan (SET plan) [4] that directs energy research and development towards improving the performance of existing renewable technologies and developing a new generation of low carbon technologies [10].

The Heat Road Map Europe 2050 pre-study [11] specifies combined heat and power and district heating as a technological tandem that enables transition to de-carbonized heating by providing improved energy efficiencies and supporting further integration of renewable sources. Whilst this technological approach can be deployed in cities that accommodate 57% of the European population with at least one existing district heating system supply, there are countries such as Ireland and UK where these systems are rarely used [11].

It is widely accepted that renewable sources can provide a secure and reliable supply of lower or zero emission energy [12], [13], [14]. Although it is expected that green technologies will become increasingly more competitive as fossil fuel prices rise and renewable technologies mature, the initial investment is typically greater as they are generally

more capital intensive [12]. Hence, further Low or Zero Carbon (LZC) emitting technologies research, development and deployment are required to define cost effective solutions and to encourage their diffusion and deployment [15].

Latest reports [16] on existing gaps in RD&D of clean energy for building and industry acknowledge that although improved technologies have already demonstrated the required performance, they are often more expensive than traditional fossil fuel based systems and are not optimized for the widest range of applications and climates. Hence there is a need for further efforts on LZC energy technologies, particularly on their integration and system optimization for different applications. Moreover, literature shows that while individual technologies can benefit from global R&D efforts, supplementary work should be carried out to adapt system designs and practices to local norms and climate as technology integration and demonstration must be country and even region specific [16], [17].

This HP-HRES-IRL research study addresses the identified gaps and proposes a methodology for optimum design and operational control of thermal hybrid renewable energy systems that combine renewable and sustainable energy sources to supply heat to buildings and industrial process applications operating in Ireland's cool marine climate [18]. It employs intelligent data mining and system analysis tools such as artificial neural network (ANN) and genetic algorithm (GA).

2. Definition and problem formulation

2.1. Hybrid system definition

Renewable energy is derived from available sources that are naturally replenished continuously or within a time span of a few years such as solar, aero- or geothermal and wind energy [19]. Renewable energy resources tend to be sustainable, although biomass or bio-fuels sustainability is controversial [20]. LZC technologies are employed to harness the natural renewable energy for human benefit as useful energy services [21]. Renewable Energy System (RES) is defined as interconnected energy supply and demand system based on renewable energy as opposed to fossil or nuclear fuels [19].

Literature defines a Hybrid Renewable Energy System (HRES) as that consisting of one or more renewable sources, combined with or without conventional energy sources in order to provide

useful electrical or thermal energy services [22], [23]. Such a HRES is shown in Figure 1 which also represents the system constructed in this study to provide space heating to the two contrasting applications. Given that heat pumps have a controllable output capacity with little dependence on the weather conditions, they can deliver a variable, yet dependable and sustainable energy supply. Hence, such systems are addressed as Heat Pump based HRES (HP-HRES) and since the study was conducted in Ireland the HP-HRES-IRL project acronym is used.

Many authors consider that while a single-source renewable energy system has the potential to either partially or totally cover some basic energy needs, it is often achieved at high cost due to a need for over-sizing the single-source supply to meet specified availability and/or reliability requirements [21], [22]. The alternative options of hybridizing the renewable single-source system with another renewable energy source or a conventional source, have been shown to lower capital/running cost and improve overall performance [21], [24], [25], [26], [27], [28].

The most relevant performance indicator of a HRES is the Renewable Energy Fraction (REF). It is defined as the percentage of the total energy demanded by and delivered to the load in a certain period of time (i.e. one year) that derives from renewable. Other indicators include the usability of the installed renewable capacity which represents the percentage of the total harvestable solar or wind energy that is delivered to and used by the load.

Due to their improved performance thermal HRES are nowadays considered and utilized for community level applications. In Denmark, the SUNSTORE 4 project involves the development of the renewable energy supply system with a 100% REF for the 1600 strong community of Marstal [29]. The system consists of a solar plant, seasonal heat storage, heat pump and a biomass boiler as part of an innovative and cost efficient energy supply system. Another good example is represented by the Drake Landing Solar Community project in Alberta, Canada where a thermal HRES supplies space heating to 52 houses at 90% REF [30].

The methodology presented in this study was developed, tested and validated using two smaller yet different applications but the authors acknowledge the potential and need for extending its applicability to larger community or regional projects.

Figure 1. Flowchart of the hybrid renewable energy systems used in this HP-HRES-IRL study

2.2. Problem formulation

Designing an optimum HRES is complicated by the large number of variables to be considered and the non-linear characteristics of the RES, which includes both predictable and unpredictable components. Therefore, diverse and high levels of skill and scientific judgment are required to produce cost effective functional and reliable energy supply systems [31], [32].

Finding the optimum HRES is achieved by selecting the appropriate system configuration and component sizes, and combining these with suitable operational control strategy and settings. The operating strategy adopted in managing the hybrid system combined with the sizing choice affects the system performance as well as the degradation of components [24], [26].

The design of thermal HRES can be formulated as an optimization problem as follows ([26], [31]):

Given a set of:

- Thermal energy demand(s) of a target application
- Meteorological or other associated data regarding renewable energy sources in a certain geographical area
- Technical and economical data for the individual units required to harness, store and transform energy in the considered system
- Performance measure(s) for the HRES.

Determine:

- The design options, both structural (e.g. capacity of individual components) and operational (e.g. parameters of the operating strategy), that optimize the defined system performance measure(s).

Subject to constraints involving:

- The cost and performance requirements of the targeted application
- The feasible system operation.

The methodology presented in the next section helps to identify the most promising energy system configurations given availability and demand data.

3. The HP-HRES-IRL Methodology

3.1. Overview

An iterative approach has been taken within this HP-HRES-IRL study to find the optimum HRES design. The problem has been modeled as a decision making process which involves elements such as decision alternatives, events or states of nature and consequences associated with each decision alternative as well as event outcomes.

HRES design options which constitute the decision alternatives in the decision making process, are described by system and operation variables, parameters and constraints as shown in Figure 2.

Energy demand and weather data depict the states of nature while evaluation of consequences involves system design modeling and simulation. The optimum design is identified by assessing the consequences of various system alternatives against optimization goals while meeting the specified system constraints.

The structure of the HP-HRES-IRL methodology is presented in Figure 2 and represents a system analysis that uses artificial intelligence (AI) tools which are widely accepted as techniques offering alternative ways to tackle complex and ill-defined problems [33]. They also have the potential to model and replicate expert knowledge required in engineering design tasks [34], [35], [36], [37].

Figure 2. Hybrid system design methodology framework employed in HP-HRES-IRL

AI tools have already been successfully deployed in the RES design field. The ANN has been reported as an useful tool for modeling mainly single source electrical and thermal RES and also predicting certain weather parameters or energy demand [38], [39], [40]. GA has also been reported as a valuable optimization tool mainly for single source RES and electric power based hybrid systems [22], [41], [24], [39], [27], [42].

3.2. System sizing

The HP-HRES-IRL methodology uses a hybrid AI technique that employs ANNs for system modeling required to perform a GA search to identify the optimum system design including components size. A similar approach was suggested to analyze solar based industrial process heat and large hot water systems operating in Cyprus [32], [41]. However, the HP-HRES-IRL methodology facilitates the evaluation of multiple renewable and sustainable energy sources in Ireland's highly variable maritime climate conditions. It allows the best combination and size of renewable energy supply technology to be established by offering a systemic analysis as opposed to an individual component analysis.

3.3. Operational control

Defining the best combination and size of energy sources is further enhanced by the optimum operation control. HP-HRES-IRL considers the operational control flow displayed in Figure 3 which prioritizes energy flows from solar and wind sources while attempting to optimize heat pump operation when capacity to store energy exists. This operational control optimization routine is reduced to finding the appropriate storage state of charge (SOC)

that maximizes the daily and seasonal performance of the whole system. SOC defines the charge level as a percentage of the maximum storage capacity.

Figure 3. Hourly optimum operational control for a heat pump based HRES

Within the HP-HRES-IRL methodology, 24 operational optimization variables have been defined as representing the optimum storage SOC for each

hour of the day. The 24 optimum hourly SOC values make up the daily operation control tableau. Monthly, seasonal and yearly tableaux are then identified when short, medium and seasonal storage is considered. All tableaux can be combined into HP-HRES-IRL operation control parallelepiped shown in Figure 4

Figure 4. HP-HRES-IRL operation control parallelepiped

4. Implementation and validation

4.1. Design parameters and software tools

The HP-HRES-IRL methodology shown in Figure 2 was used to analyze a heat pump based hybrid thermal system supplying low grade thermal energy to two contrasting applications: an 1125m² commercial building (LiBC) and an 8000 litre aquaculture facility (TESSA). Both systems comprise the LZC technologies specified in Figure 1. The simulations and modeling were performed using performance parameters specific to three technologies operated by GMIT: Proven 6 wind turbine, TC Mach Chameleon 8.3 air source heat pump and Zhejiang Shentai – SCM 20 evacuated tubes solar thermal collector. Irish price estimates from 2010 were also used for each of these technologies.

The methodology was implemented using spreadsheet tools. Data were analyzed using Neural Tools and Evolver supplied in the Decision Tools Suite by Palisade Corporation. Neural Tools employ Multi-Layer Feed-forward Neural Networks (MLFN) which offer greater reliability outside the training range and capable of generalizing from small training datasets [43]. Evolver uses GA to search for optimal solutions to linear, non-linear, table-based or stochastic numerical problems [44].

4.2. Climate and energy demand data

Optimum sizing and operational control of hybrid energy systems requires solutions to manage hourly, daily and seasonal fluctuations of the renewable energy system output derived from the solar or wind components of the local weather conditions [19], [45]. Three key weather parameters are usually considered when predicting the likely output of such systems, namely ambient air temperature, solar radiation and wind speed [38], [46] as identified in Figure 2.

In the HP-HRES-IRL study presented in this paper, weather data for 2008 and 2009 have been measured using GMIT's weather station [47], [48]. Sample data from 2008 are presented in Figure 5.

Thermal energy consumptions of LiBC building, and the TESSA re-circulating aquaculture facility have also been monitored over this period, as shown in Figure 6 and Figure 7. Note, that both applications required similar annual amounts of energy for space heating, 48MWh in LiBC and 42MWh in TESSA.

The LiBC building was used mainly during the day and comfortable conditions were necessary in the building. TESSA facility required a 20°C constant indoor temperature throughout the year. The proportion of the energy demanded in LiBC between April and September (outside the traditional space heating season) was only 12% of the total, whereas TESSA required 35% of the total energy to be delivered outside the traditional space heating season.

Figure 5. Hourly averages for air temperature, solar irradiation and wind speed measured at GMIT in 2008

a) Hourly energy demand in IiBC 2008

b) Hourly energy demand in TESSA 2009

Figure 6. Measured hourly space heating demand of the two trial applications

Figure 7. Seasonal distribution of the thermal energy consumption for both trial applications

Both the weather and demand recorded data shown in Figure 5 and Figure 6 have been used for developing and testing the HP-HRES-IRL methodology.

4.3. ANN modeling

ANNs were used to predict REF or usability of renewable capacity for various HRES configurations. Approximately 600 alternatives of heat pump based HRES, matching 100% the energy demand, have been simulated using experimental data recorded for both weather and low grade thermal energy consumption of the IiBC building in 2008 and TESSA aquaculture facility in 2009. The training data comprise a random selection of 80% of the simulation results. The remaining 20% were used to test the network. MLFN architecture was used and the number of nodes in the input and hidden layers was varied between 2 and 20 to search for the best ANN configuration. Although a higher number of nodes generally led to better prediction accuracy, it also required longer training time as indicated in Table 1.

The error distribution shows that the residuals concentrated around zero value for most of the cases for both datasets. Sample accuracy and distribution of errors on the test data set are illustrated in Figure 8

a) and b). Similar results were observed for IiBC trial application.

Table 1. Sensitivity between number of nodes and training time when employed to search for the best ANN configuration to predict REF - TESSA 2009 (only the first 4 of 19 MLFNs are presented)

Net Architecture	RMS	Training time
MLFN 2 Nodes	0.02973	00:07:14
MLFN 3 Nodes	0.01750	00:08:40
MLFN 4 Nodes	0.01341	00:11:10
MLFN 5 Nodes	0.00978	00:15:42

For the example in Table 1, the 18 node MLFN exhibited the best accuracy of estimations on training and testing datasets as shown in Figure 8.

a) Predicted vs. simulated REF on testing dataset

b) Distribution of error on the testing dataset

Figure 8. Comparisons between ANN predicted and simulated REF for the HRES supplying thermal energy to TESSA in 2009

4.4. GA system optimization

4.4.1. Energy mix, system sizing and capital cost.

GA searches were conducted in order to find the optimum system configuration for both applications. System variables such as solar panel area, number of wind turbines and both heat pump and storage capacity were used in the optimization process. Constraints such as total area of solar panels that cannot exceed the area of the building's flat roof were used in specifying variable ranges to limit the search space. Hard constraints such as a certain REF to be delivered by the hybrid system have also been imposed on the GA optimum search. The optimization goal was defined as a combination of design variables and parameters, for instance minimize capital cost as a function of component size and cost parameters.

Capital cost minimization was conducted for both the IiBC and TESSA heat demands and local weather data recorded during 2008 and 2009 respectively. Single or multiple energy source constraints have been considered; GA search settings included a population size of 100 and a time limit of 30 minutes imposed for search duration.

The capital cost per percentage of REF achieved by the system, defined as the normalized capital cost, has been found to reach its minimum when all three renewable sources, “All renewable”, are available for consideration, either individually or in combination with one another. The normalized cost baseline is derived from the cost of “All renewables” systems as shown in Figure 9. The “Only solar” or “Only wind” refer to systems including just on-site solar or wind energy generation.

Figure 9. Increase of normalized capital cost for single and multi-source HRES achieving desired renewable energy

Normalized capital cost increase is defined as:

$$\frac{\text{normalized cost} - \text{normalized cost baseline}}{\text{normalized cost baseline}}$$

Figure 9 highlights the potential to avoid significant capital cost when multi-source energy systems are considered in certain situations. Relying solely on wind driven immersion heater alternative seems to be the most expensive solution for both applications for REFs lower than 80%. It also shows that single technologies such as grid powered heat pump systems can only achieve up to a certain relatively low fraction of renewable energy. The results also revealed that there are situations in which optimized single-source systems can require the lowest capital cost especially when relatively low fractions of renewable are sought. Results also give a roadmap of progression from low REF values towards 100%.

4.4.2. Energy system layout. Three HRES layouts or operation modes have been considered in this study as follows:

- Mode 1: onsite wind turbine energy used directly with immersion heaters – no electricity export to the power grid
- Mode 2: onsite wind turbine energy used via heat pump and electricity grid assisted – no electricity export to the power grid
- Mode 3: onsite wind turbine energy used via heat pump and electrical grid integrated – excess electricity export to the grid is possible.

HP-HRES-IRL methodology has been employed to assess various system layouts in supplying heat energy to both trial applications and results are shown in Figure 10 a) and b). As expected, the normalized capital cost tends to grow as renewable energy fraction increases.

Figure 10. Normalized capital cost vs. REF in different operation modes

Comparing applications in Figure 11 and Figure 12 at 10% desired REF, normalized cost is less for TESSA as the annual energy requirements is 12.5% smaller than the IiBC. As desired fraction of renewable energy increases from 10% to 50% normalized cost increases by 93% for IiBC and 49% for TESSA. The difference in the increase rate can be explained by the higher energy consumption at certain times by the IiBC application.

The capital cost was calculated based on the recommended system configurations shown in Figure 11 and Figure 12. As an example of reading these figures, the yellow highlighted section from Figure 11 shows that for the IiBC trial application the lowest capital cost HRES, operating in mode 1 and achieving 50% REF, should comprise 77 m² of solar collector area, no wind turbine, no heat pump and 322 kWh of thermal storage capacity.

Also Figure 11 and Figure 12 demonstrate the capacity of HP-HRES-IRL methodology to generate

a clear image of the technology options when incrementally increasing the REF within energy system. Additionally, the methodology allows to identify “anomalies” such those highlighted in green showing that combinatorial optimization can lead to higher component size at lower REF than the size required at higher REF. For instance, as shown in Figure 11- highlight 1, 150m² of solar collector area are required for the optimum system configured in mode 1 to supply 80% REF for the LiBC test application. At 90% REF, only 70 m² of solar collectors are required for the same application. Similar observations can be made about heat pump capacity or thermal storage size with system layout set to mode 2 and 3. Anomalies can be identified for TESSA trial application as well. This kind of information supports decision making for a positional HRES optimization that not only provides the optimum system configuration for a certain REF but also puts the system into a position favorable to further REF increase.

It can be noted that onsite wind technology is not part of the optimum system configurations at REF lower than 40% for LiBC and 70% for TESSA, hence there is no impact of the system layout on the capital cost. In fact, in mode 1, the wind technology becomes part of the optimum solution at higher than 80% REF. This reflects the relatively “inefficient”, one to one use of wind resource as opposed to being multiplied via a heat pump. Also seasonal storage never became part of the optimal solution even at high REF due to the 5% daily loss imposed on the thermal storage.

Figure 11. Optimum solar, wind, heat pump and thermal storage size for LiBC 2008 achieving REF up to 90%

Figure 12. Optimum solar, wind, heat pump and thermal storage size for TESSA 2009 achieving REF up to 90%

When achieving high REF, the capital cost of the HRES grows rapidly especially with the system configured in mode 1 and 2. This again proves the high challenge of achieving near to 100% REF.

4.4.3. GA search validation. The optimum GA search was compared against a random search for optimum system configuration as shown in Figure 13. The random search was achieved through:

- discretization of the design space: the four dimension design space was considered to comprise 1,812,500 distinct system configurations resulting from:
 - total solar collectors area: up to 250 collectors of 1.6 m²/collector
 - number of wind turbines of up to 5 turbines
 - capacity of thermal store: 29 values – 11 short term storage up to 250kWh, 9 medium term up to 2500kWh, 9 long term up to 25000kWh
 - heat pump rating: up to 50kW
- randomly sampling the design space: a 50,000 sample was selected containing randomly selected distinct system configurations
- evaluation of the sample: 1.5 seconds processing time was required for one simulation – therefore 20.8 processing hours were required to evaluate the entire sample

- grouping and ranking of the results: the system configurations in the sample were grouped by simulated REFs and ranked by capital cost. The minimum cost configuration was identified for REF between 10% and 90%.

As displayed in Figure 13, the HP-HRES-IRL produced better results than those generated by the random search. The ordinate of the blue bubble center represents the cheapest capital cost system identified by the random search and the ordinate of the maroon dot represents the minimum normalized cost generated by the HP-HRES-IRL search. The radius of the blue bubbles is proportional to the number of system configurations from the random sample achieving a REF of at least the corresponding abscissa value, but not higher by more than 10%.

Figure 13. Minimum normalized capital cost resulting from GA search and from random search of a 50,000 random sample of the discretized design space

4.4.4. Fine tuning of system operation.

Alongside optimum energy mix, sizing and layout, appropriate operation control provides the potential for further enhancement of a HRES. Several selected system configurations were simulated in order to assess the potential benefits of operational control fine tuning. For instance, a 25kW air source heat pump in conjunction with short-term (250kWh), medium-term (2500 kWh) and seasonal (25000 kWh) thermal storage was considered to supply heat to both trial applications.

The HP-HRES-IRL methodology was employed in finding the optimum values for the hourly state of charge as shown in Figure 14 through Figure 16.

The optimum hourly SOC values were identified for each month as shown in Figure 14. It can be noted that the higher optimum SOC values occurred around

the time of the day at which the air temperatures are near to the daily maxima.

Figure 15 shows that higher optimum SOC values were advised near the midday in autumn and winter seasons. That suggests that the search algorithm identified correctly the higher chance of colder temperatures to follow in the autumn season and coming into winter season.

Figure 14. Optimum hourly SOC values with short-term thermal storage (250kWh)

Figure 15. Optimum hourly SOC values with medium term thermal storage (2500 kWh)

The SOC values displayed in Figure 16 were obtained when seasonal storage was considered for both applications. The results were application specific as difference can be noted in both magnitude and time distribution.

Figure 16. Optimum hourly SOC values with seasonal thermal storage (25000 kWh)

Simulation of the heat pump based energy system accounting for optimum SOC values determined earlier identified potential Seasonal Performance Factor (SPF) and REF improvements as indicated in Figure 17 a), b), c). SPF of a HRES is defined as the total energy supplied to the load over a period of time divided by the amount of conventional energy (i.e. electricity) consumed within the system during the same period of time. The reference values for both REF and SPF were simulated for null optimum SOC values and are provided in Table 2.

Table 2. Reference REF and SPF annual values for LiBC 2008 and TESSA 2009 with energy supplied only on demand - no storage

Energy Systems	REF	SPF
LiBC 2008	32%	3.68
TESSA 2009	31.56%	3.65

While the optimized control based on short-term storage proved to generate an improvement that mainly follows day-to-night air temperature fluctuations, it also showed a significantly lower improvement during the summer when energy demand is weaker. Seasonal optimal SOC values used with medium term storage showed higher potential for system performance improvement in the transition from summer to winter than vice-versa. The highest overall performance improvement of up to 18% has been exhibited by the long-term storage configuration for the TESSA trial application as illustrated by Figure 17 c).

a) Monthly change resulting from usage of short-term thermal storage (250 kWh)

b) Seasonal change resulting from usage of medium-term storage (2,500 kWh)

c) Seasonal storage (25,000 kWh)

Figure 17. Increase in the REF and SPF of heat pump based RES when optimum SOC values are identified for short, medium term and seasonal thermal storage capacities

5. Conclusions

This paper proposes the HP-HRES-IRL methodology to optimize energy mix, component sizing, system layout and operational control of a heat pump based hybrid renewable energy system. The methodology employs artificial intelligence such as ANN for HRES modeling and uses GA for optimum solution search. Computational intelligence tools have been reported previously as suitable tools for hybrid electrical and single source thermal RES and applications located in various climates. This study demonstrates that their use can be extended to multi source thermal renewable energy systems.

HP-HRES-IRL methodology has been successfully demonstrated for two different trial applications in the highly variable Ireland's cool marine climate. It can be used to identify minimum capital cost combinations of HRES in order to meet specific REF between 0 and 100%. The results

obtained after a 30 minute GA search proved to be better than a 20.8 hour evaluation of a large sample of the discretized design space.

The methodology showed:

- sensitivity to the application with different combinations and size of energy supply solutions being suggested for both trial applications
- sensitivity to the climate with the benefit of increased performance that accrues from different thermal storage capacities and operational control
- sensitivity to components performance/characteristics

The methodology also facilitates further refinement of the HRES by fine enhancement of the system operation.

The methodology can facilitate a technological roadmap towards a 100% REF systems based on combinatorial optimizations that can be further used to support positional system optimization.

Further validation may be achieved by using this methodology with other applications. The methodology should be expanded to support decision making in relation to community or regional energy systems.

6. References

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