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Multiobjective optimisation of integrated energy systems for remote communities considering economics and CO_2 emissions

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Abstract

The methods for designing, planning and managing integrated energy systems, while holistically considering the major economic and environmental factors, are still embryonic. However, the first phase of the design is often crucial if we want to manage resources better and reduce energy consumption and pollution. Considering integrated energy systems implies dealing with complex systems in which the synergy between the various components is best exploited (for example the thermal energy of a diesel engine produced during the night is complimented by the Rankine organic cycle of a solar thermal plant). The context of isolated communities further increases the difficulties when considering the long distance of transport required to supply fossil fuels. These sites are often located in very precarious environments, with limited or nonexistent resources except for solar energy, and with frequent additional needs for desalination (in arid zones).

This paper illustrates a holistic method to rationalize the design of energy integrated systems. It is based on a superstructure (collection of models of all envisaged technologies) and a multi-objective optimisation (resources, demand, energy, emission, costs) using an evolutionary algorithm. The approach proposed allows the identification of more complete and more coherent integrated configurations characterizing the most promising designs (also taking into account the time dependency aspects). It also allows to better structure the information in view of a participative decision approach. The study shows that the economic implementation of renewable energy (solar) is even more difficult, compared to diesel based solutions, in cases of isolated communities with high load variations. New infrastructure or retrofit cases are considered.

Keywords: Multi-objective optimisation; Diesel generators; Photovoltaic; Rankine cycle; Heat storage; Energy systems; CO_2

1. Introduction

Currently, remote communities are often supplied with electricity by diesel generators complemented with photovoltaic systems. The main problems with diesel generators, are emissions, the fact that the resources are not renewable, logistics and noise. Simulations have been made of a remote community in the Tunisian Sahara to see the effects on the choice of power technologies when pollution and economic considerations are taken into account.

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2. Situation and data

The considered site is an oasis of 150 ha, located 150 km from the closest urban centre. It is composed of a village (200–400 inhabitants), and four hotels (max. 530 beds, average occupancy 90 beds) [1]. One of these hotels is a four star hotel with air-conditioned Berber tents and a swimming pool. The geographic layout of the oasis is shown in Fig. 1.

All the hotels have a highly variable occupancy rate during the year and throughout the day [1]. The resulting electricity consumption is schematically shown in Fig. 2 either with the actual consumption or with a potential of maximum occupancy of the hotels throughout the year. The peak demand corresponds to summer months with air conditioning (Table 1).

Nomenclature

c	non-dimensional constant	
C	cost	EUR
C_{tot}	total cost for n_y years	EUR
C_τ	actualised cost	EUR
E	electrical energy	kWhe
$\dot{E}$	electrical power	kWe
g	mass	g
Δh_i^o	lower heating value of the diesel, $= 42\,600$	$\text{kJ}\cdot\text{kg}^{-1}$
$I_{\text{sun}}(t)$	total sun radiation at the time t	$\text{kW}\cdot\text{m}^{-2}$
L	load of the engine	
$\dot{M}$	flow rate	$\text{kg}\cdot\text{s}^{-1}$
n_y	number of years, $= 20$	
Pt_J	loss percentage due to Joules effects, $= 0.025$	
$Pt_{\text{O\&M}}$	loss percentage due to maintenance, $= 0.05$	
Pt_{Other}	loss percentage due to other, $= 0.025$	
$\dot{Q}^{-}_{\text{cond}}$	heat power in the condenser of the ORC	kW
S	surface	m^2
T	temperature	K
$T \times I$	interest rate, $= 0.12$	
V	volume	
Y	value of the function	

Greek symbols

ε	first law efficiency

Subscript

atm	atmospheric
C	carbon
CHP	combined heat and power (diesel engines)
CP	parabolic collector
CT	cooling tower
d	diesel
g	exhaust gas
HC	unburned hydrocarbons
HR	heat recovery
HS	heat storage
M	diesel engine
MG	diesel engine and generator
N	nominal value
ORC	organic Rankine cycle
O&M	operation and maintenance
PV	photovoltaic panel
Tot	total
var	variable

Abbreviation

MOEA	multi-objective evolutionary algorithms
NDS	non-dominated set
QMOO	queuing multi-objective optimiser

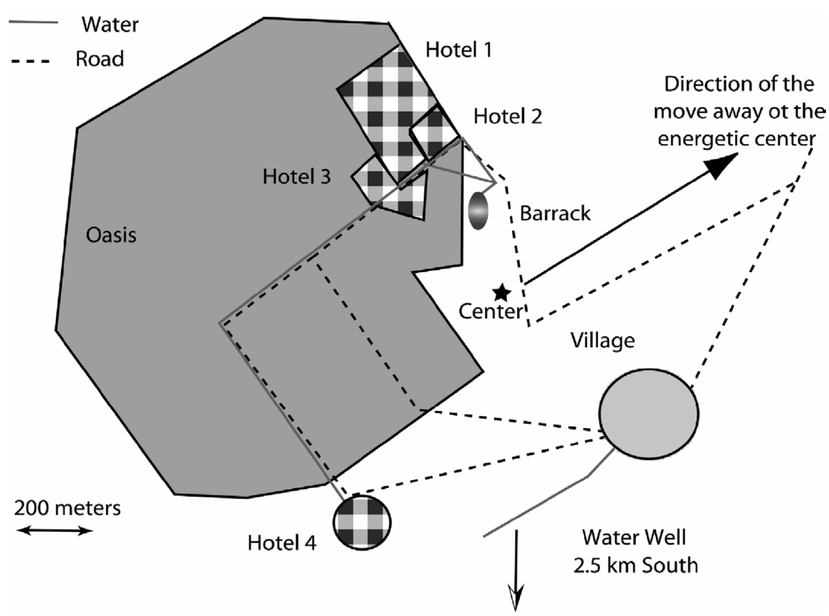

Fig. 1. Present situation [1].

The electrical needs are modelled by taking twelve representative days of each month and five especially busy days. The latter is done to avoid using monthly average for the peak month which would not be representative of the real peak demand.

Currently, like many villages in developing world, this oasis is not connected to the main grid and has no electric grid

Table 1
Electrical parameters of the village consumption

Units [kWe]	Average	Min	Max
Present electrical needs	53	27	88
Max. potential electrical consumption (if the hotels were full all along the year)	203	74	679

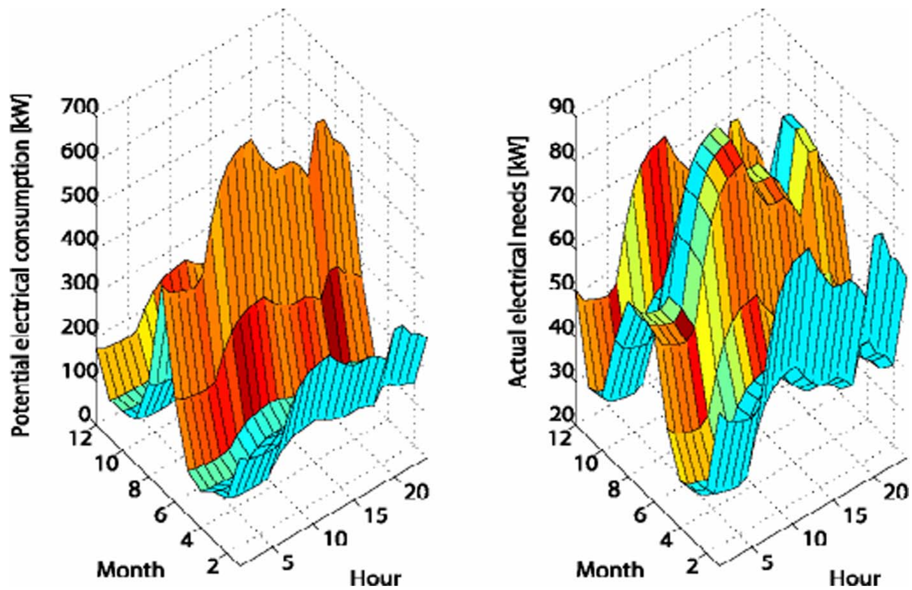

Fig. 2. Variation of the maximum (potential with full occupancy of the hotels) and present electrical consumptions (with highly variable occupancy throughout the year) [1].

between the hotels and inside the village except for a link between two hotels. Each hotel has two generator groups. The fuel is supplied by road. There are individual photovoltaic panels on the roofs of each house in the village which are not connected together. An additional array of 27 m^2 of photovoltaic panels is used to feed a down-the-hole water pump. During some periods there is a lack of electricity in the village and for the pumps, while there is excess electricity in the hotels. This excess exists because the generator sets cannot, according to the constructor's specifications, run at a power lower than 25% of their nominal power.

3. Model superstructure

Simulations of the community energy infrastructure are based on a superstructure in which all technology options to be potentially considered are included in the form of the following modules: Diesel engine (co-)generators, photovoltaic panels (PV), organic Rankine cycles (ORC), electrical grids, heat storage (HS), cooling towers and solar parabolic trough collectors (PT) (Fig. 3). For each component the model includes the most significant factors such as thermodynamic behaviour, economic trends as well as gaseous and noise emissions.

The diesel generators can be used alone or in cogeneration mode, the latter implying extra investment costs for the heat exchangers. The hypothesis is made that only the heat from the exhaust gas can be used by the organic Rankine cycle (the use of engine block cooling as in [2] could be considered in the future). Additional heat can be produced by solar trough collectors. Heat can be used directly by the organic Rankine cycle or stored in a stratified heat storage system.

A number of variables are used to specify how the system is controlled. These variables are:

- The part of the maximal nominal power that is supplied by the engines or the ORC.
- The total number of engines.
- The number of engines that are equipped for cogeneration.
- The number and nominal power of the engines in stand-by to meet occasional peaks.
- The average percentage of power production attributed to engines.
- The average percentage of power production based on heat storage.
- The upper temperature of the ORC (150–170 °C).
- The lower temperature of the ORC (90–120 °C).

The basic formulation of the model allows the location of the equipment to be inside or outside the oasis area (when noise is considered). In the present study this noise penalty is not considered but the location of the equipment can be specified according to their present locations (for retrofit) or all equipment can be considered to be at the central location indicated in Fig. 1. No special gas post treatment systems have been considered to actively reduce emissions.

4. Thermoeconomic models

It is important to note that the following values are averages of data found in the literature or given by equipment suppliers. Often a large scatter in the values can be noticed. More information about the variance of the costing models is given in [1].

4.1. Diesel generator sets

The thermodynamic model of the diesel generator sets has been made from manufacturers' data on the basis of a database of more than 450 engines. The following functions indicate an average of the assumed performance of the diesel generators, based on the lower heating value Δh_i^o of the fuel [3].

$$Y = c_0 + c_1\left(\dot{M}_d \Delta h_i^o\right)^{c_2} + c_3 \ln\left(\dot{M}_d \Delta h_i^o\right)$$

with the parameter values given in Table 2. Table 3 gives the parameter values for the following equation valid for the estimation of the heat rate, which can be recovered from the engines at nominal load:

$$Y = \sum_{i=0}^{2} c_i \left(\dot{M}_d \Delta h_i^o\right)^i + c_3\left(\dot{M}_d \Delta h_i^o\right)^{c_4}$$

Table 4 gives the parameter values for the following equation valid for the estimation of the CO emissions from engines:

$$Y = C_0 + C_1 \dot{M}_d \Delta h_i^o + C_2 \log\left(\dot{M}_d \Delta h_i^o\right)$$

A value for total unburned hydrocarbons (HC) between 0.1 et 2 g·kWhe^{-1} is found in the literature [4–7]. In our case a value of 0.44 g per kWh (5.2 milligrams per gram of fuel) is considered.

The mass flow of CO_2 is given by:

$$\dot{M}_{CO_2} = \frac{44}{12}\left(M_d^{C}\dot{M}_d - \frac{12}{16}\dot{M}_{HC} - \frac{12}{28}\dot{M}_{CO}\right)$$

For partial load, the results of experimental analyses from a given engine supplier were extrapolated to the others and summarized in Table 5 for the physical parameters and performance and in Table 6 for the emissions.

Existing installations were taken to approximate the investment cost function for Diesel engines [8]:

$$C_{CHP} = 6543.6 \dot{E}_{M}^{0.6941}$$

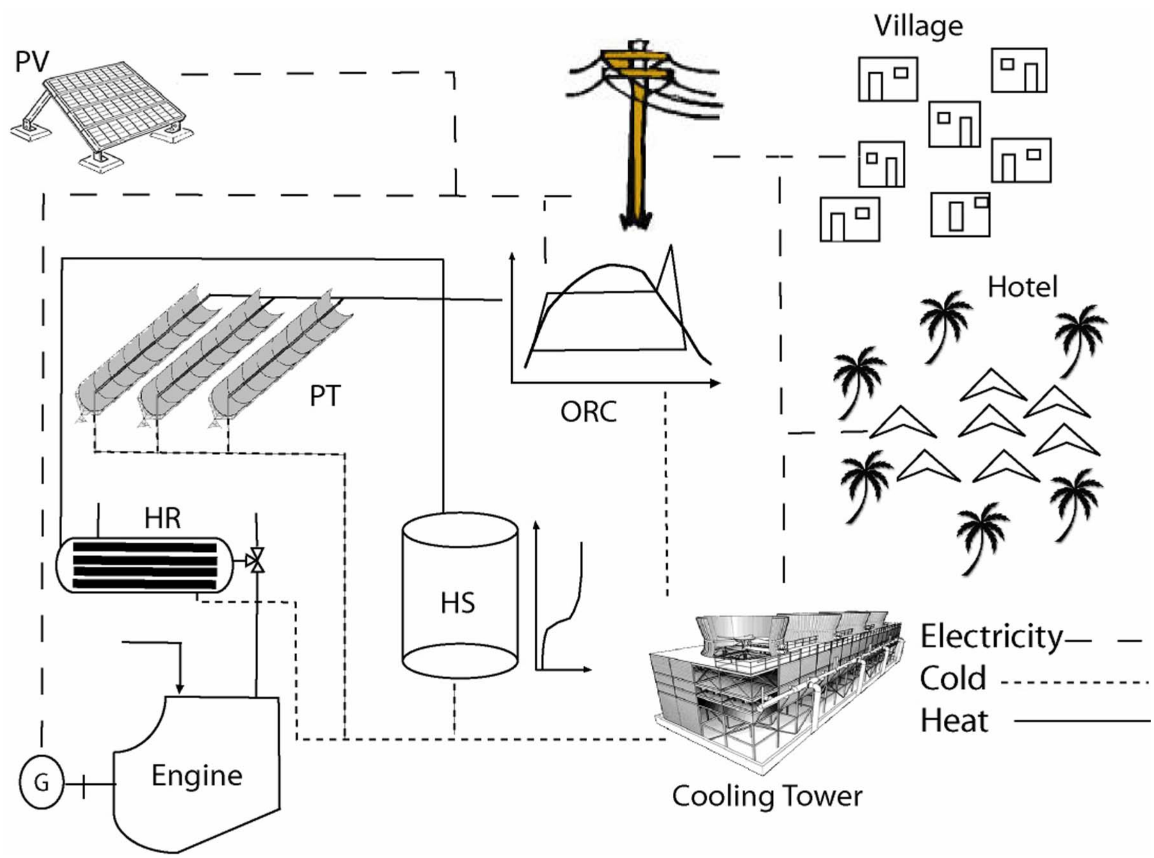

Fig. 3. Superstructure of the technologies considered.

Table 2
Model parameters for nominal load of diesel engines

Y	c_0	c_1	c_2	c_3	Validity [kW]
ε_{MG_N}	0.376	0	0	0.0146	$4.8 \times 10^3 < \dot{M}_d \Delta h_i^o < 5 \times 10^4$
	0	0.2252	7.04×10^{-2}	0	$35 < \dot{M}_d \Delta h_i^o < 4.8 \times 10^3$
ε_{M_N}	0.338			0.0123	$10^3 < \dot{M}_d \Delta h_i^o < 5 \times 10^3$
		0.3427	3.02×10^{-2}		$35 < \dot{M}_d \Delta h_i^o < 10^3$
$\dot{M}_{g_N}$		2.01×10^{-3}	1		$35 < \dot{M}_d \Delta h_i^o < 5 \times 10^3$
T_{g_N}	273.1	795.71	-6.27×10^{-2}		$70 < \dot{M}_d \Delta h_i^o < 5 \times 10^3$

Table 3
Model parameters of the recoverable heat rate (for engines at nominal load)

Y	Unity	c_0	c_1	c_2	c_3	c_4	Validity [kW]
$\dot{Q}_{\text{ref}_\text{N}}$	kW	−6.1925	0.2331	2×10^{-5}	0	0	$200 < \dot{M}_d \Delta h_i^o < 5000$
		0	0	0	0.393	0.9061	$35 < \dot{M}_d \Delta h_i^o < 200$
$\dot{Q}_{\text{rad}_\text{N}}$	kW	0	0	0	0.5708	0.7111	$35 < \dot{M}_d \Delta h_i^o < 5000$

Table 4
Parameter values for CO for engines

Y	Unity	C_0	C_1	C_2	Validity
CO	g_{CO}/g_d	−14.203	0	2.7623	$769.2308 < \dot{M}_d \Delta h_i^o < 5000$
		2	0	0	$35 < \dot{M}_d \Delta h_i^o < 769.2308$
		9.525	4.185×10^{-5}	0	$5000 < \dot{M}_d \Delta h_i^o < 50\,000$

Table 5
Physical parameter values for engines at partial load $Y = \sum_{i=0}^{4} c_i L^i$

Y	c_0	c_1	c_2	c_3	c_4
$\varepsilon_\text{M}/\varepsilon_{\text{M}_\text{N}}$	0.4457	2.7093	−5.2738	4.6718	−1.551
$\varepsilon_\text{G}/\varepsilon_{\text{G}_\text{N}}$	1[a]	0	0	0	0
T_g/T_{g_N}	0.2022	1.664	−1.0986	0.2291	0
$\dot{M}_g/\dot{M}_{g_\text{N}}$	0.5441	−0.6429	2.8421	−2.7865	1.0423
$\dot{Q}_\text{rad}/\dot{Q}_{\text{rad}_\text{N}}$	0.202	0.1421	0.7211	0	0
$\dot{Q}_\text{ref}/\dot{Q}_{\text{ref}_\text{N}}$	0.1518	0.8382	0.0061	0	0

[a] The efficiency of the electric generator is only weakly influenced by the load and is here considered constant [8].

Table 6
Engine emissions at partial load $Y = \sum_{i=0}^{6} c_i L^i + c_7 L^{c_8}$

Y	$\dot{M}_{CO}/\dot{M}_{CO_N}$	$\dot{M}_{CO_2}/\dot{M}_{CO_{2N}}$		$\dot{M}_{HC}/\dot{M}_{HC_N}$
Range		$L > 0.225$	$0 < L < 0.225$	
c_0	15.513	0.97563	1.0900	0
c_1	−116.49	0.96592	−0.17	0
c_2	3.5838	-3.5107×10^{-2}	0	0
c_3	-5.3991×10^{-2}	4.0458×10^{-4}	0	0
c_4	3.9666×10^{-4}	-1.4781×10^{-6}	0	0
c_5	-1.13×10^{-6}	0	0	0
c_6	0	0	0	0
c_7	0	0	0	9658.7
c_8	0	0	0	−0.983

$$C_\text{HR} = 0.6534\dot{E}_\text{M}^{-0.1323} C_\text{CHP} \quad \text{if } 10 < \dot{E}_\text{M} < 100$$
$$C_\text{HR} = 1.8183\dot{E}_\text{M}^{-0.3377} C_\text{CHP} \quad \text{if } \dot{E}_\text{M} > 100$$

The operating functions were taken from [9]:

$$C_{\text{CHP O\&M}_\text{fixe}} = -0.0016\dot{E}_\text{M}^2 + 18.048\dot{E}_\text{M}$$
$$C_{\text{CHP O\&M}_\text{var}} = (C_\text{oil} + C_\text{Maint} + C_\text{Usury})E_\text{M} + C_\text{diesel}\int_0^{1\text{year}} \dot{M}_d(t)\,\mathrm{d}t$$

with a diesel cost

$$C_\text{diesel} = 0.366 \ [\text{EUR}\cdot\text{kg}^{-1}]$$
$$C_\text{Maint} = 1.71 \times 10^{-3} \text{ maintenance cost } [\text{EUR}\cdot\text{kWh}^{-1}]$$
$$C_\text{oil} = 1.74 \times 10.\text{e}^{-3} \text{ cost of lubrication oil } [\text{EUR}\cdot\text{kWh}^{-1}]$$
$$C_\text{Wear} = 2.13 \times 10^{-3} \text{ cost of wear } [\text{EUR}\cdot\text{kWh}^{-1}]$$

4.2. Organic Rankine cycle

The following equations were taken to model an organic Rankine cycle [2,10,11] on the basis of a prototype of ORC using hermetic scroll expander-generators:

$$\dot{Q}^-_\text{cond} = 1.7108\dot{E}^-_\text{ORC}(T_{\text{Turb}_\text{in}} - 273.15)^{-0.1346}$$
$$C_\text{ORC} = 13194\dot{E}_\text{ORC}^{-0.977} \quad \text{if } \dot{E}^-_\text{ORC} < 3.5$$
$$C_\text{ORC} = 4700.2\dot{E}_\text{ORC}^{-0.2395} \quad \text{if } 3.5 < \dot{E}^-_\text{ORC} < 10^4$$
$$C_\text{ORC} = 4868.2\dot{E}_\text{ORC}^{-0.2038} \quad \text{if } \dot{E}^-_\text{ORC} > 10^4$$

4.3. Photovoltaic

Photovoltaic (PV) panels were modelled from [12,13]:

Table 7
Reduction of efficiency of photovoltaic panels as a function of the ambient temperature

T [°C]	−20	−10	0	10	20	30	40
$\Delta\varepsilon_T$	1.2	0.8	0.4	0.01	0.001	−0.8	−1.2

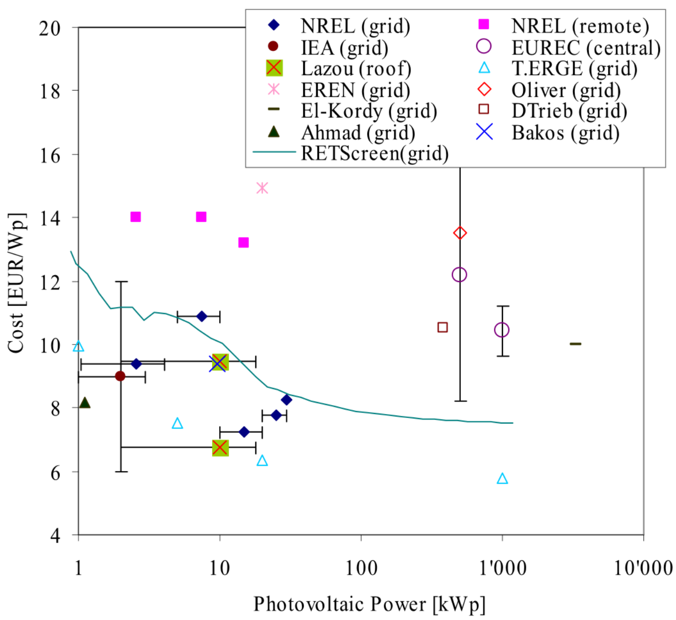

Fig. 4. Cost of photovoltaic power plants.

$$\varepsilon_{PV} = \frac{I_{sun}(t)S_{PV}}{\dot{E}_{PV}} = (\varepsilon_{PV_N} - \Delta\varepsilon_T)\varepsilon_{CE}(1 - Pt_J)(1 - Pt_{O\&M}) \times (1 - Pt_{Other}) \quad \text{with}$$

$\varepsilon_{PV_N} = 0.12$

$\varepsilon_{CE} = 0.9$ efficiency of power conditioning[1]

$\Delta\varepsilon_T$: variation of efficiency due to the ambient temperature

(See Table 7.)

The literature gives different costs for photovoltaic installations (Fig. 4). Strong differences were found between different sources. Country, years of warranty, VAT, existing or project installations partially explain these differences. For this optimisation the model RETscreen [12,13] was taken. It allows to account more precisely for the characteristics of the country considered and for the particular situation of the oasis (distance, salaries...).

4.4. Solar trough collectors

The solar trough collector is modelled from the characteristics of the Luz model LS3 and the thermodynamic model was taken from [2].

The cost is given by:

[1] Electronic devices to control the PV array and transform its DC output to AC.

$$C_{CP} = S_{CP}\left[c_{land} + 317.93\left(\frac{S_{CP}}{1e^4}\right)^{0.1035}\right] \quad \text{with}$$

$c_{land} = 0.64$ specific land cost [EUR·m^{-2}]

If $S_{CP} < 470\,000$ [m^2]

$C_{CP_{O\&M}} = -3.10^{-5} S_{CP} + 22.036$ [EUR·year^{-1}]

else $C_{CP_{O\&M}} = -3.10^{-6} S_{CP} + 10.039$ [EUR·year^{-1}]

4.5. Heat storage

The cost function for the heat storage is based on models from [14,15]:

$$C_{HS} = c_1\left(\frac{V}{V_r}\right)^m$$

with

V [m^3]	C_1 [DKK] [2]	V_r [m^3]	M
< 100	22 800	1	0.78
$\geqslant 100$	63 000	1	0.5593

The operating cost is estimated to be 3% of the investment costs [16].

4.6. Cooling tower

The thermoeconomic model for the cooling tower was taken from [17].

4.7. Other

The value of 12 100 [EUR·km^{-1}] is taken for the electrical grid, and an operating cost of 10% of the initial cost is taken. Other costs due to elements such as buildings, electrical transformers and heat networks are considered. They play a marginal role and are not analysed here.

5. Objective function

The choice has been made to pursue the analysis using a two-objective function optimisation. The first objective function used in all analyses and represented in abscise of the Pareto diagrams, is the total cost which here includes the cumulated investment cost for all components over a duration period of 20 years plus the operational cost. The second objective function varies according to the various analyses but in this paper, is limited to the cumulated CO_2 emissions. Results with other objectives like the cumulated noise or the life cycle assessment according the CST method are presented elsewhere [1]. The general formulation of these objective functions is the following:

$$C_\tau = f_\tau(C_{CHP} + C_{HR} + C_{ORC} + C_{CP} + C_{HS} + C_{CT} + C_{Other})$$

[2] Exchange rate (2002) 1 DKK = 0.13213 EUR.

with f_τ the factor of actualisation

$$f_\tau = 1 + \frac{T \times I}{1 - (T \times I + 1)^{n_y}}$$

$$C_{\text{tot}} = C_\tau + n_y(C_{\text{O\&M}_\text{CHP}} + C_{\text{O\&M}_\text{HR}} + C_{\text{O\&M}_\text{ORC}} + C_{\text{O\&M}_\text{CP}} + C_{\text{O\&M}_\text{HS}} + C_{\text{O\&M}_\text{CT}} + C_{\text{O\&M}_\text{Other}})$$

When analysing CO_2 as an objective function, only the CO_2 emitted by the engines during operation is considered by opposition to a full life cycle accounting.

6. Multi-objective evolutionary algorithm

The queuing multi-objective optimiser (QMOO) used here was developed in Refs. [18,19]. Like other multi-objective evolutionary algorithms (MOEAs), it allows the optimisation of several objectives. By keeping the objectives separate, trade-offs between different objectives are clearly illustrated, and more informed design decisions can be made. In this case it allows to find and rank the best integrated generation technology solutions from the superstructure, which are both cost effective and less polluting. The solutions returned by the algorithm are an approximation to a Pareto-optimal front—such a solution cannot be made less polluting without being more costly, or cheaper without emitting more.

QMOO has a number of features (described in detail [18,19]) that distinguish it from other MOEAs. It is extremely elitist, to the point of preserving the entire non-dominated set (NDS), resulting in fast convergence. For calculation improved efficiency it includes strategies to "thin" the NDS if the large set becomes unmanageable, to the point where these methods can result in better performance than preserving the entire NDS. It is also unique because it uses statistical classification methods to identify and preserve different clusters of solutions, resulting in an effective search for multiple local optima, and consequently a good chance of converging to the global optimum. QMOO also features an architecture that makes it easy to perform objective function evaluations in parallel on a cluster of workstations, greatly reducing the elapsed time for convergence.

The strategy adopted here is to establish first the configuration and design followed by the optimisation of the operation. The decision variables are percentages of the yearly use of the technologies and iterations are made to find the nominal values (Fig. 5). The average and maximal electrical demands are calculated from 12 typical days of 24 hours (Fig. 2). The technologies are dimensioned from the maximal power demand and the operation is optimized according to the average demand.

Four variables $P_{\text{ORC-Mot}}$, P_{CP}, P_{stock}, P_{Mot} determine the percentage of the production of the ORC connected to the engines, of the ORC in connection with solar trough collectors, of the heat from the heat storage with the ORC, or of the engines.

Other decision variables are added to these variables to precise additional characteristics of the technologies like:

- P_{SB} part of the energy of the engines used in stand-by. $N_{\text{Mot.SB}}$ fixes the number of engines in stand-by. N_{Mot} the number of engines to supply the rest of the demand. E2 the nominal power of the N_{Mot}.
- $P_{\text{ORC\_NbreMot}}$ number of engines equipped for cogeneration.
- $P_{\text{orc-CP}}$ surface of the parabolic trough collectors.
- $P_{\text{Stock-use}}$ parameter defining the strategy of supply from the heat storage.
- T_{MT} and T_{HT} are the temperatures of the stratified heat storage.

For the simulation the priority is given to the use of the renewable energies if the investment has been done accordingly (Fig. 5). In a first step photovoltaic supply is subtracted from the total demand curve. The next step is to find by iteration the nominal values of the technologies to fit to the electrical percentages $P_{\text{ORC-Mot}}$, P_{CP}, P_{stock}, P_{Mot}. If there are no physical solutions able to achieve these percentages, they are modified to meet with the closest feasible solution. Finally the objectives values are calculated.

7. Results when optimising for low CO_2 emissions

The goal of our study has been to optimise various alternatives of either retrofit or of new design in different situations (increase of the diesel cost, fixed location)

Fig. 6 shows the Pareto curves resulting from the optimization based on CO_2. Each point corresponds to one solution (one genome or set of variables). With the present equipment and strategies of operation, the annual emissions of CO_2 are estimated to correspond to 863 tonnes which is about twice as high as the emissions related to solutions (1) in Fig. 6 and Table 8. A retrofit case shows that the cheapest solution (1) is to connect with a local grid, all the electrical utilities available on the site (which result in a reduction of 51% of CO_2 and 33% of cost). Then the next solutions for decreasing the CO_2 are based on engines in cogeneration mode with an ORC and are about 3% more costly. To further decrease the CO_2 emissions the use solar trough collectors is required (4.2% more costly). Then with a cost overrun of 6%, solutions with engines in cogeneration, ORC and solar trough collectors appear along the Pareto curve.

With a new design (at present fuel cost), the cheapest but the most CO_2 emitting solution (2) includes only engines. The next alternative solutions (between (2) and (3)) (more expensive but emitting less CO_2) include engines used in cogeneration and an ORC (from 4% more expensive). Then solar trough collectors are found in the next order of solutions (started from solution (3)) together with a more powerful ORC. It is only when the cost is allowed to double that heat storage systems appear among the dominating solutions.

This synthetic way of presenting results allows an easy evaluation of the level of CO_2 taxes which should be introduced to favour the emergence of given renewable solutions. In Fig. 7, the ordinate value for each solution (each point of the diagram) is calculated using the following equations:

$$C_{\text{Tax}_{\text{CO}_2}} = \frac{C^x_{\text{Tot}_{20\,\text{years}}} - C^0_{\text{Tot}_{20\,\text{years}}}}{\int_0^{20\,\text{years}} \dot{M}^0_{\text{CO}_2}\,\mathrm{d}t - \int_0^{20\,\text{years}} \dot{M}^x_{\text{CO}_2}\,\mathrm{d}t} \quad [\text{EUR}\cdot(\text{tonne of CO}_2)^{-1}]$$

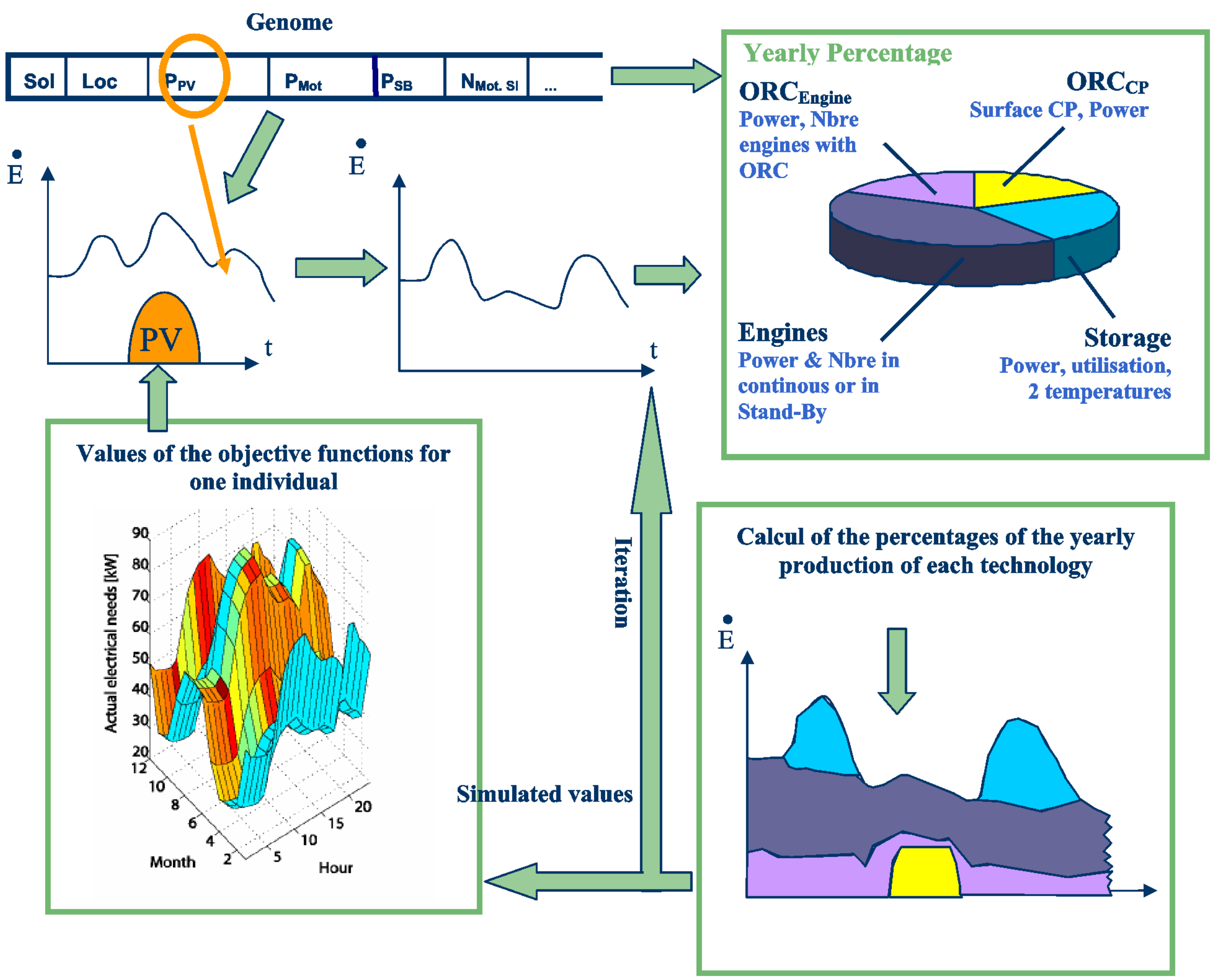

Fig. 5. Hierarchical refinement of the solution (genome) based on physical and temporal constraints.

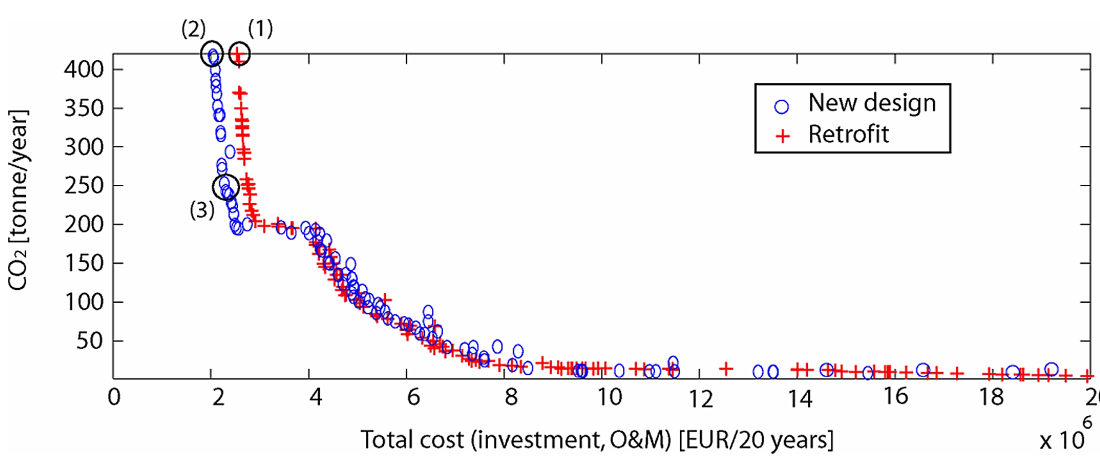

Fig. 6. Comparison of the yearly emissions of CO_2 in the case of a new design and of a retrofit optimisation. The solutions (1)–(3) are further described in Table 8.

or

$$C_{\mathrm{Tax}_{\mathrm{Diesel}}} = \frac{C^x_{\mathrm{Tot}_{20\,\mathrm{years}}} - C^0_{\mathrm{Tot}_{20\,\mathrm{years}}}}{\int_0^{20\,\mathrm{years}} \dot{M}^0_d\,\mathrm{d}t - \int_0^{20\,\mathrm{years}} \dot{M}^x_d\,\mathrm{d}t}$$

$[\mathrm{EUR}\cdot(\mathrm{kg\ of\ diesel})^{-1}]$

where the total cost $C^x_{\mathrm{Tot}_{20\,\mathrm{years}}}$ and $C^0_{\mathrm{Tot}_{20\,\mathrm{years}}}$ for respectively the solution "x" or the presently most economic solution "0" do not yet include the cost increase related to either a CO_2 tax or a fuel tax.

In the case of the CO_2 tax, each point "x" of Fig. 7 is the threshold of tax from which the solution is more economical than the presently most economical solution. This translates

Table 8
Parameters of four solutions in case of a CO_2 analysis

Solutions	Present	Retrofit (1)	New design (2)	New design (3)
Engine [kWe]	2 × 27/40/300	2 × 27/40/300	2 × 88/592	2 × 75/548
PV [kWe]	11	11	0	0
ORC [kWe]	0	0	0	56
Engine [kWhe/y]	3.84×10^5	4.35×10^5	4.58×10^5	2.54×10^5
PV [kWhe/y]	2.26×10^4	2.26×10^4	0	0
ORC [kWhe/y]	0	0	0	2.07×10^5 [a]
		Cost of the energy[b]		
Engine CI [EUR/kWhe]	0.125	0.110	0.081	0.136
Cogeneration engine [EUR/kWhe]	–	–	–	0.011
Engine O&M [EUR/kWhe]	0.308	0.119	0.118	0.131
Engine [EUR/kWhe]	0.432	0.229	0.200	0.277
ORC [EUR/kWhe]	–	0	–	0.102
CT [EUR/kWhe]	–	0	–	0.038
PT [EUR/kWhe]	–	0	–	0.042
PV [EUR/kWhe]	0.40	0.4	0	–
Other [EUR/kWhe]	0.035	0.039	0.035	0.035
Total [EUR/kWhe]	0.466	0.276	0.235	0.270
Total cost [EUR]	3.79×10^6	2.53×10^6	2.15×10^6	2.70×10^6
CO_2 [tonnes/year]	863	420	416	246

[a] Around 13% of this energy is linked to the heat recovery on the engines.
[b] Attributed to the power producing units per kWhe.

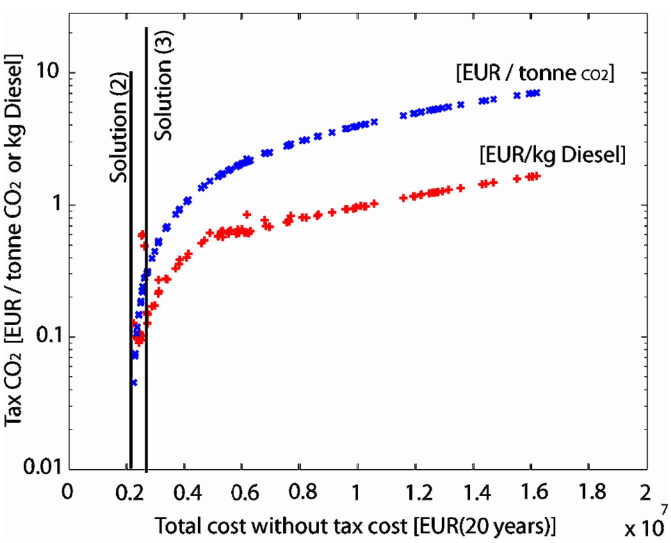

Fig. 7. Sensitivity of a variability threshold to a CO_2 tax or a fuel tax for the case of a new design (20 years over).

into the following equation:

$$C^0_{\mathrm{Tot}_{20\,\mathrm{years}}} + C_{\mathrm{Tax}_{CO_2}} \int_0^{20\,\mathrm{years}} \dot{M}^0_{CO_2}\,\mathrm{d}t$$

$$= C^x_{\mathrm{Tot}_{20\,\mathrm{years}}} + C_{\mathrm{Tax}_{CO_2}} \int_0^{20\,\mathrm{years}} \dot{M}^x_{CO_2}\,\mathrm{d}t$$

A reduction of 40% of CO_2 emissions requires a tax of around 2 [EUR·(tonne of $CO_2)^{-1}$], which correspond to a tax of 0.15 [EUR·(kg of diesel$)^{-1}$] and a 20% cost overrun (Fig. 7 solution (3)). Note that the fuel tax can be interpreted as an increase of fuel cost and that sensitivity can be very useful when oil prices are substantially changing.

The above example shows the advantage of such a method which allows an easy ranking of all the best solutions based on economic and environmental considerations. The breakeven point for renewable energies is highlighted and measures to encourage their implementation through pollution taxes for example can be rationally assessed.

8. Conclusion

This paper illustrates a holistic design and planning method particularly valuable for complex integrated energy systems which include a large number of parameters. The method allows a quantitative assessment of key economic and ecological parameters when comparing and ranking solutions. A representation of the optima along a Pareto curve provides an overview of the best part of the solution field which can be determined using an efficient multi-objective algorithm. The results of a case study of an isolated oasis show that even in extremely favourable solar conditions, solutions including solar power production either from thermal or photovoltaic conversion units were not economically viable with the oil price of the 90th or beginning of the 21st century. The main reason was the difficulty for investment intensive solar or storage technologies to efficiently respond to highly variable loads when not connected to a main grid.

However the proposed method allows an easy assessment of the sensitivity of the solutions to changes in fuel prices or to the introduction of a CO_2 tax. Both retrofit and entirely new solutions have been illustrated. A simple retrofit solution includes a local electrical grid between the present utilities resulting in a reduction of 33% on cost and 51% in CO_2 emissions. A further cost reduction with an entirely new design has been shown for equivalent CO_2 reduction. Sensitivity analysis to cost, in the case of a new design, allows to explore further CO_2 reduction and the economic penalties associated with them. One interesting solution for the chosen case study allows to reduce CO_2 emissions by 40% with only a 25% cost increase.

The method is highly modular and can be extended to new sites as well as to other parameters like life cycle indicators or new technologies and services.

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