PROCEEDINGS OF ECOS 2023 - THE 36TH INTERNATIONAL CONFERENCE ON
EFFICIENCY, COST, OPTIMIZATION, SIMULATION AND ENVIRONMENTAL IMPACT OF ENERGY SYSTEMS
25-30 JUNE, 2023, LAS PALMAS DE GRAN CANARIA, SPAIN

# *Decarbonisation & Optimization Strategies in Distributed Energy Community characterized by Demand of Electricity, Cooling, and Heating*

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**Abstract:**
The global call for an environmentally friendly, sustainable and reliable distributed energy community is gaining traction nowadays, pushing the scientific community to explore novel multi-energy system layouts for highly decarbonised design. The complexity of highly integrated systems resides in selecting the components optimal capacities and establishing the demands for electricity, cooling and heating. While traditional fossil-based centralised distribution is not affected by intermittencies of renewables, highly decarbonized decentralised energy communities need to cope with the variability – in the short and long term – of renewables and the end-users demands. The scientific community addresses this problem by integrating various energy storage technologies in the energy community, but the selection of the most suitable technology and the related optimal capacity requires advanced optimisation tools capable of simulating years of the system operations, including stochastics factors that affect prices, costs and carbon taxes and regulations. The authors developed over the last five years the DECAPLAN™ Digital Platform capable of solving master-planning and optimal dispatch strategy problems. DECAPLAN™ includes hybrid heuristic/deterministic algorithms, based on a Genetic/MINLP solver, for establishing the optimal energy community design in respect of financial indicators, such as NPV, ROI and CO2 per year. In the paper, the authors present a real case in the Mediterranean Tropic region, showing a sensitivity analysis of the effect of environmental policies on the whole system design. Results in terms of energy community optimal component selection and optimal dispatch strategy are presented together with a sensitivity analysis on the effect of fuel and CO2 tax prices variability over the next decade.

**Keywords:**
Decarbonization, Master-Planning, DECAPLAN™, Distributed Energy Community, Optimization

## 1. Introduction

Scientists are calling for an energy transition [1] which must confront the limitations of reality , and specifically address the inadequate infrastructures that currently exist. The electricity sector is the primary focus of this transition, as evidenced by the significant increase in the installation of electric renewables over the past two decades [2], which has largely been achieved through a centralized approach that involves connecting new renewable energy power plants to the grid. While this has reduced the Primary Energy Factor of the Power Grid, it has also placed additional stress on the grid due to the influx of new energy production [3]. To address the balancing issues that result from the mismatch between energy demand and production, storage facilities have been included, but their limited size and high costs have impacted the grid's operation [3, 4, 5]. In light of this, it is necessary to consider the energy balance at the national level as the sum of smaller-scale energy balances, highlighting the crucial role of local Distributed Energy Communities (DECs) [16] in achieving a more balanced and sustainable energy mix [7, 8, 9]. By reducing changes and stress on the grid infrastructure, local energy communities can focus on local emission factors linked to energy mixes [10], leading to a decentralized search for renewable energy plants and the establishment of Renewable Energy Communities codified in the EU Directive REDII. Additionally, incentive schemes supporting Self-Consumption aim to provide community members with shared added value in terms of environmental and financial impacts throughout the energy chain [12, 13].

Solar PV and Solar Collectors on the roof, hot water storage, electric batteries in the basement are the most used tools made available to the citizens to participate to this new entity. Beside them, innovative technologies are taking place such hydrogen energy systems. Similarly, centralized approach for assisting the Grid is taking place first even with the limitations in size and impact due to the high costs. Later, small scale hydrogen energy

https://doi.org/10.52202/069564-0183

systems are seeing interest thanks to devices like the reversible fuel cells offering the production and utilization of hydrogen as a service for the buildings and in cooperation with other sectors like the mobility.

The integration of DECs in the existing infrastructure is a challenge faced by the scientific community in the last decade and affects the large scale DECs development due to some limitation such as the Capital Investment Cost, the Intermittency and variability of the renewable energy resources, the limited capacity related to the site-specific conditions and also on the technical challenge of integrating DECs into the existing grid. Indeed, to accommodate the DECs power generation it could be required to upgrade the grid infrastructure and may involve significant regulatory and policy changes.

Furthermore, in order to answer the call for higher decarbonization DECs, the integration of multi-energy highly integrated systems allows for drastically reduction in CO2 emissions but not necessarily in a easy-to-implement techno-economic manner. Accordingly, the selection of the most suitable technology and the related optimal capacity requires advanced optimisation tools capable of simulating years of the system operations, including stochastics factors that affect prices, costs and carbon taxes and regulations. The authors developed DECAPLAN™ digital platform capable of solving master-planning and optimal dispatch strategy problems. DECAPLAN™ includes hybrid heuristic/deterministic algorithms, based on a Genetic/MINLP solver, for establishing the optimal DEC design in respect of financial & environmental indicators, such as NPV, ROI and CO2 emitted per year. In the paper, the authors present a real case in the Mediterranean Tropic region, showing results in terms of energy community optimal component selection and optimal dispatch strategy, together with a comparative analysis on the achievable Operating Cost (OPEX) savings and CO2 emission reductions related to DEC configuration complexity.

## 2. Technical Background

The role of citizens regarding energy consumption and production has progressively changed during the last years. From passive energy consumers, they have become "prosumers" or active energy consumers because they both consume and produce energy, mainly through the installation of photovoltaic (PV) panels on their rooftops [14]. Renewable Distributed Energy Communities (DEC) can be defined as a group of prosumers composed of diverse users (e.g. individual households, municipal bodies, private businesses etc.) who share power plants for the generation and self-consumption of electricity, cooling and heating from renewable energy sources [15]. The diffusion of Renewable DECs produces benefits in terms of sustainability, costs and safety [16, 17] because DECs show:

- Localized generation of highly decarbonized electricity, cooling and heating, concurrently reducing $CO_2$ emissions, fuel poverty and energy losses during distribution.
- reduced grid fees and energy costs;
- flexibility of the energy usage due to the integrations of energy storage technologies for allowing peak shaving operations at DECs level.

DECs are also characterized by social innovation because they reinforce support between citizens and encourage their participation towards climate neutrality and energy transition through a democratic control over energy investments [18].

### 2.1. Existing Distributed Energy Community and the reference case

Renewable Distributed Energy Communities are progressively spreading in Europe, mainly in Germany, Denmark and Netherlands [18]. Italy is still characterized by a much lower number of active communities, equal to around 20 [19, 20].

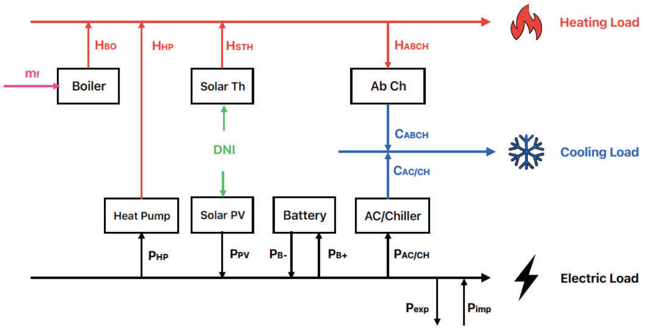

**Figure 1.** Schematic representation of the Renewable DEC of this study

According to literature [18 - 21], solar technologies are the most common used in Renewable DECs. Indeed, solar panels and solar collectors allows for quick and easy-to-customize installations suitable for rooftops of different buildings such as households, public buildings, and farms. Another important characteristic of existing energy communities is in the local production and consumption of energy, combined - when possible - with a variety of end-user uses of energy with the aim to match demand and generation, minimizing energy import/export from/to the power grid.

In this paper, the authors model and investigate the environmental and economic viability of different configurations of a Renewable DEC located in the Mediterranean Tropic region (latitude of around 37° 35' 59.9784"), where solar availability is relatively huge. The Renewable DEC is made up taking the main features of a real DECs and the overall demands of heat, domestic hot water, electricity, and cooling into consideration. The DEC account for a real municipality of around 350-400 inhabitants

The load demands of electricity, heating and cooling have been evaluated by considering that the DEC serves different types of users. Indeed, specific load profiles for different destination of usage have been combined, and mainly are related to:

- a shopping center with a supermarket, a coffee bar and a chemist's.
- a sport club.
- a town hall.
- 200 households

The authors present different DEC configurations (case studies A1 – E5), based on the DEC layout given in figure 1, varying the equipment technology and related installed capacity for supplying the end-users needs.

The DEC layout modelled by the authors and adopted for running the simulations is depicted in figure 1 together with the equipment providing for the generation and consumption of the required end user demands in terms electricity, heating and cooling. Indeed, the system has been modelled in buses as described below:

- Electricity Bus: Solar PV ($P_{PV}$), Battery Discharge ($P_{B-}$) and Power imported from the grid ($P_{imp}$) are the positive contribution for the positive terms for the electric load generation, while Heat Pump ($P_{HP}$), Battery Charge ($P_{B+}$), Air-condition/Chiller System ($P_{AC/CH}$) and power exported to the grid ($P_{exp}$) are negative ones.
- Heat Bus: Natural Gas fed Boiler ($H_{BO}$), Heat Pump ($H_{HP}$) and Solar Thermal Collector ($H_{STH}$) are contributing to the satisfaction of the Heat Load demand ($H_{Load}$), while Absorption Chiller ($H_{ABCH}$) is reducing the $H_{Load}$ generation, for supplying the Cooling Load ($C_{Load}$).
- Cooling Bus: the $C_{Load}$ is supplied by AC/Chiller ($C_{AC/CH}$) and by the Absorption Chiller ($C_{ABCH}$) cooling generation equipment.

The DEC can import and export electricity from or to the grid in case of lack or excess of production from the installed plants in the community, as shown in Figure 1.

## 2.2. The sensitive Parameters characterizing DECs

As mentioned in Paragraph 2, DEC can serve different kinds of end-consumers and related needs. Accordingly, the load demands of electricity, domestic hot water, cooling, and heat of the community are obtained by combining each of the load demands related to the various end-users in the DEC. Indeed, each consumer has specific load demands [22], which vary on the basis of the time period of the day and of the week (e.g. working days and holidays), the month of the year and the season. Other factors impacting on the load curves are [23, 24]:

- building size and architecture, looking at gross floor area (GFA) ($m^2$) and volumetric extension ($m^3$);
- building energy class and the related energy efficiency policies for planning;
- differentiation between regions and countries in terms of climate (e.g. DNI, ambient temperature, relative humidity), economic conditions and Technology Level (e.g. developed countries have a lower number of people per household).

In previous scientific works, the authors presented a deep analysis of the load demands from industrial [25, 26], commercial and domestic users [27-29]. In this study, the total demand of the DEC is evaluated by taking both the in-situ analyses performed in previous works and the available data referred to European municipalities located at the same latitudes of the DEC [25-29] into consideration.

Figure 2 shows - the normalized electricity load profiles of a typical winter working day related to the different users for being part of the proposed DEC. The type of user determines different trends: the shopping centre shows a practical constant load during the day, both the sports club and the households have the load peak during the evening, while the town hall shows his peak in the morning.

The DEC is modelled according to available data of real municipalities in the Mediterranean tropic region in terms of number, floor area and volumetric extension of households, buildings and facilities [30, 31].

https://doi.org/10.52202/069564-0183

The generation side is evaluated considering the values of temperature and solar irradiance at the latitudes of the DEC [32, 33]. An optimization of the design of the community structure is executed grouping diverse types of users with the aim of matching demand and generation curves, reducing energy export to the external grid.

The assumptions and the DEC architectural features are presented to perform the analysis to evaluate the load demands (electricity, cooling, and heating) of the DEC, it is important to understand how the boundary conditions (namely temperature and DNI) and the buildings/infrastructure configuration influences the heat/cold gain of the system and as well the electrical consumption. Indeed, based on the general specific daily load profile given in section 2, in the specific case scenario the DEC serves four diverse types of users, namely households, a shopping centre, a sports centre and a town hall, supplying electricity, domestic hot water, heat and cooling. According to the proposed case study located in the Mediterranean area, the authors have summarized in Table 1 the main characteristics of the community's buildings, while in Table A.2 shows the number of families with the number of family members living in the community.

The yearly temperature and DNI distribution for the given location, have been retrieved by MARRA-2 Data base. The yearly curves for the different load demands and different type of user are evaluated thanks to DECAPLAN™ Digital Platform by finetuning the parameters on the basis of the data derived from literature [34], that account for the variability of the demands supply during the day, week and month. As an example, the aggregated load demands of electricity, cooling and heating for a typical week during the winter (January) and during the summer (July) have been presented in figure 3 by the authors.

**Table 1.** DEC Buildings Architectural Characteristic

| Type of building | Floor surface [m$^2$] | Volumetric extension [m$^3$] |
|---|---|---|
| Real estate district | 13,590 – 13,600 | 40,770 – 40,780 |
| Shopping centre | 820 – 830 | 2,900 – 2,910 |
| Sports centre | 710 – 720 | 2,140 – 2,150 |
| Town hall | 230 - 240 | 700 - 710 |

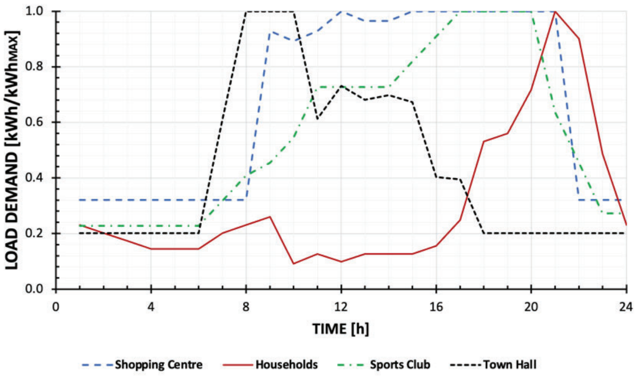

**Figure 2.** Electricity Load Demands for different DEC user during a typical winter working

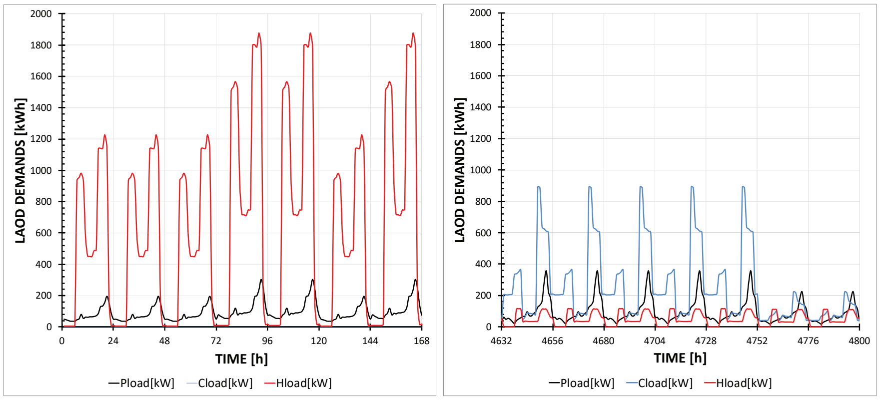

**Figure *3.*** Typical Load Demands Profile during winter (left) and summer (right) for reference case study.

## 3. Materials and Methods

In this section, the methods used for data collection, modeling and analysis are described. The DECAPLAN™ digital platform [34-37] is proprietary software of MEDS Venture Global Pte Ltd start-up company spin-off of Nanyang Technological University. The DECAPLAN™ Digital Platform has been developed by the authors over the last five years for designing power plants, microgrids, and industrial and building estates characterised by high energy mix by establishing the best plant arrangement and choosing among database (DB) the most suitable commercially available components. The DECAPLAN™ allows for concurrently optimising the best multi-energy plant design and operation by solving the energy dispatch (unit commitment) problem for given electricity, cooling and heating demands. In this paper, the optimal solution is addressed to minimise the primary energy consumption and the greenhouse pollutant emissions ($CO_2$) by minimizing them at the same time. The mathematical formulation of the DECAPLAN™ objective function enables the digital platform to search for the best solutions taking the Operational Expenses (OPEX), the Localized Cost of Electricity (LCOE), the Return of the Investment (ROI), and other parameters into consideration. More details on the modelling approach and the optimisation strategy are given in the next section. The proposed system layout includes several DEC components such as Solar PV, Solar Cooling, Heat Pumps, Chillers, Energy Storage Technologies (namely battery in the specific DEC) and others as well as their part-load off-design maps for optimized asset management.

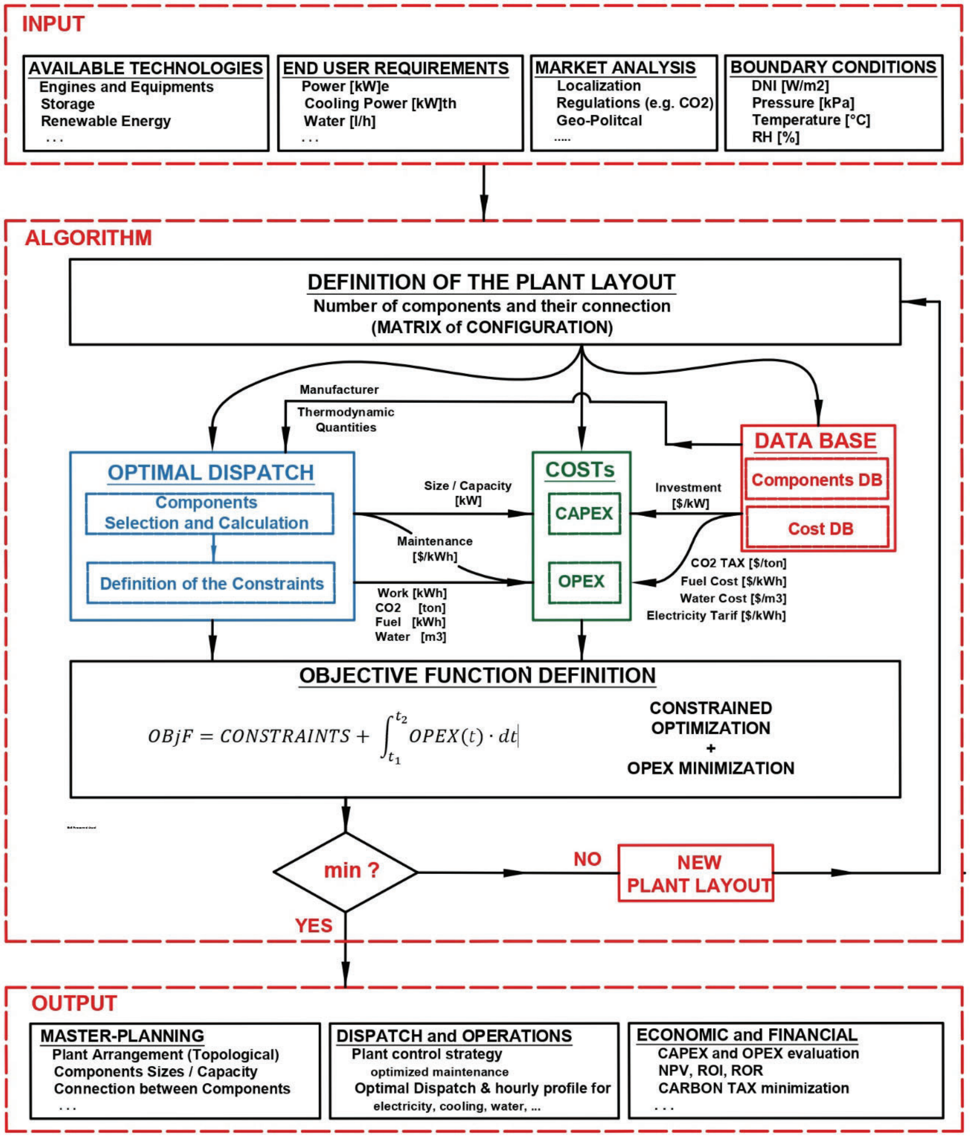

**Figure 4.** The functional block diagram of DECAPLAN™ digital platform

Details on the mathematical formulation for the Master Planning (MP) and the Optimal Dispatch Planning (ODP) are discussed by the authors in [36, 37], while for purposes of this work the functional scheme with the description of the main features of the DECAPLAN™ digital platform is summarized below. The simulation tool for the DEC system was developed using a modular approach at the component level. To set up the DEC simulator, steady-state 0-D component models were adopted as per the method proposed by the DECAPLAN™ digital platform algorithm. The DECAPLAN™ includes various solvers such as quadratic programming, mixed-integer linear programming (MILP), and mixed-integer non-linear programming (MINLP).

Research has shown that the mixed-integer quadratic programming technique used by the DECAPLAN™ digital platform is robust and efficient, as demonstrated by comparisons with a hybrid heuristic algorithm based on GA and PSO solvers [36, 37] and other mathematical approaches [35 - 37]. Additionally, the use of stochastic algorithms has been found to potentially lead to suboptimal results in master-planning problems [65-67]. Figure 4 provides a complementary block diagram to understand the optimization process flow that the end-users need to perform, specifically the optimal dispatch block diagram DECAPLAN™.

The algorithm consists of three parts: the *input layer*, where conditions such as temperature, DNI, and precipitation profiles, as well as plant demands and costs, are inputted; the *optimal dispatch layer*, where the algorithm matches and connects components, ensuring that conservation equations are not violated; and the *output layer*, where the optimal dispatch strategy for the power plant and its associated costs are presented. Additionally, the algorithm uses a modular approach to simulate power systems and incorporates a database of component performance maps to evaluate costs, degradation, and maintenance. Accordingly, the authors have developed ad-hoc thermal components for the specific scientific work, including solar cooling, heat pumps and thermal solar.

### 3.1 DEC Main Component Modelling

*Solar PV:* is modelled by adopting lumped performance features. The scheme of the PV model is presented in figure 6-A. The generated power PPV is calculated as (eq.1):

$$P_{PV} = DNI \cdot S_{PV} \cdot \eta_{PV} \tag{1}$$

Where DNI, SPV and $\eta_{PV}$ are the direct normal irradiance (DNI), the solar PV surface and the solar PV efficiency. The $\eta_{PV}$ in the actual conditions is established by the adoption of normalized maps developed by the authors that relates the solar PV reference efficiency, the DNI and PV cell temperature (typically referring to the panel type and to the manufacturer testing conditions) to the actual DNI and cell temperature T. The lower the cell temperature, the higher the efficiency. Typically, DB provides 0 °C as the minimum value. Accordingly, $\eta_{PV}$ is expressed functionally by (eq.2):

$$f\left(\frac{\eta_{PV}}{\eta_{PV_R}}, \frac{DNI}{DNI_R}, \frac{T}{T_R}\right) = 0 \tag{2}$$

*Solar Thermal Collector:* is modelled similarly to the Solar PV module, but as the output useful quantity is the Heat Power ($H_{STH}$) defined in (eq.3), where $\eta_{STH}$ is the STC efficiency, evaluated in similarities with the procedure of eq.2.

$$H_{STH} = DNI \cdot S_{STH} \cdot \eta_{STH} \tag{3}$$

*Heat Pumps:* the characteristic equation allowing for evaluating the useful effect $H_{HP}$ is given in (eq.4), and the details of the modelling approach are given in [35, 37], as well as per the absorption chiller and vapour compression chiller details. Off-design curves are also discussed in [35,37]

$$H_{HP} = COP_{HP} \cdot P_{HP} \tag{4}$$

*Chillers Systems:* the AC/Chiller system and the absorption chiller equations are summarized in (eq.5) and (eq.6), and the full model details can be found in [37]

$$C_{ABCH} = COP_{ABCH} \cdot H_{ABCH} \tag{5}$$

$$C_{ACCH} = COP_{ACCH} \cdot P_{ACCH} \tag{6}$$

*Fuel Boiler:* the model allows for evaluating the useful effect $H_{BO}$ (eq.7) based on the routine described in [37] for evaluating the complete combustion details of the process together with exhaust gas composition, carbon emitted.

$$H_{BO} = m_{fBO} \cdot \eta_{BO} \cdot LHV_f \tag{7}$$

*Battery:* the entire description of the model is described by the authors in [37], the main equation required for solving the ODP is given in (eq.8), where the battery energy capacity at the time-step *t+1* is evaluated as

https://doi.org/10.52202/069564-0183

function of the optimized control strategy of the battery and the capacity at the time-step *t.* For ensuring the energy conservation equation during the whole period of the battery operation, an equality constraint is introduced (eq.9).

$$E_{BATT}(t+1) = E_{BATT}(t) + P_{B+} \cdot \Delta t - P_{B-} \cdot \Delta t \quad (8)$$

$$E_{BATT}(t = t_{START}) = E_{BATT}(t = t_{END}) \quad (9)$$

### 3.2 Environmental Techno-Economic Indicators

The overall CO2 emissions are evaluated by taking into consideration the specific emission factors of the different energy generation processes, in the specific case from the import of the electricity from the national grid and from the combustion process in the fuel fed boiler. At DEC level the production of electricity from RES and export to the national grid could be expressed as a negative/avoidance of CO2 emitted and included in the evaluation. For accounting this term, that can or not included in the Scenario evaluation, the authors have adopted a ($\delta$ = 0 or $\delta$ =1) variable in the formulation. According to the above, the CO2 emissions per year are expressed by (eq.10

$$CO_2 = \sum_{t=1}^{8760}(Pimp - \delta \cdot Pexp) \cdot \Delta t \cdot f_{CO2_{grid}} + mf \cdot \Delta t \cdot f_{CO2_{fuel}} \quad (10)$$

The overall operating cost $O_{PEX}$ is evaluated as the sum of the running costs (e.g. cost of the electricity imported and fuel), maintenance cost, renting cost of the surface where installing DEC equipment and by the carbon tax, expressed by (eq.11). Accordingly, the overall OPEX, fully described in [35,37] is sinthetically expressed by (eq.12):

$$O_{CO2_{TAX}} = CO_2 \cdot TAX_{CO2} \quad (11)$$

$$O_{PEX} = O_{RUN} + O_{MAIN} + O_{RENT} + O_{CO2_{TAX}} \quad (12)$$

### 3.3 Power Constraints, Objective Function and Optimization Strategy

The solution of ODP consists of two main steps such as the minimisation or maximisation of the objective function (*ObF*) and satisfying of the equality constraints, namely electricity and cooling power flow (electricity and cooling bus load demands). From a numerical perspective, the adopted solver is based on simultaneous solutions; this means that concurrent to the equality constraints satisfaction, the *ObF* is also optimised. In the current work, the *ObF* to be maximised has been set to be the linear combination of the OPEX and CO2 emissions reduction of the k-th scenario, versus the OPEX and CO2 emissions of the reference case (REF) NPV, expressed by (eq.13).

$$ObF - Search\ MAX\ of:\ CF_k + \Delta CO2 = \left(OPEX_{REF} - OPEX_{k_{th}}\right) + \left(CO2_{REF} - CO2_{k_{th}}\right) \quad (13)$$

The satisfaction of the energy flows (operational constraints) for the economic dispatch on the electric bus is expressed by (eq.14), on cooling bus by (eq.15) and on heating bus by (eq.16).

$$P_{Load} \cdot \Delta t = P_{imp} \cdot \Delta t + P_{pv} \cdot \Delta t + P_B^- \cdot \Delta t - P_B^+ \cdot \Delta t - P_{exp} \cdot \Delta t - P_{ACCH} \cdot \Delta t - P_{HP} \cdot \Delta t \quad (14)$$

$$C_{Load} \cdot \Delta t = C_{ACCH} \cdot \Delta t + C_{ABCH} \cdot \Delta t \quad (15)$$

$$H_{Load} \cdot \Delta t = H_{HP} \cdot \Delta t + H_{BO} \cdot \Delta t + H_{STH} \cdot \Delta t - H_{ABCH} \cdot \Delta t \quad (16)$$

The formulation of the optimisation problem has been fully described by the objective function and constraints structure definition. In the next section, the test case and the analysis of the results are presented.

## 4. CASE STUDIES

The schematic representation of the Renewable DEC presented by the authors in figure 2 allows to generate multiple case studies in respect of the components included in the DEC layout and of the capacity. Furthermore, the different case studies can also be contextualized in different energy policy scenarios where Incentives, Carbon Certificates and Financial Rewards for CO2 avoidance and power generation in the DEC can be taken into consideration. According to the above, the authors have explored five DEC configurations (Layout) A, B, C, D and E, and for each of the configuration varied the number of Solar PV (0, 250, 500 and 1000), according to the maximum allowable gross floor area available for the PV installation. For the configuration C, the authors have selected the maximum number of Solar Thermal Collector of 500 unit. The matrix of the configuration generated and optimized by DECAPLAN™ Digital Platform is given in Table 3. Looking at the number in Table 2, since some of the equipment such as Heat Pumps, NG fed Boilers AC/Chiller unit splitter are specific of each unit of each building, the authors have assumed that if the component exist (N = 1) while if not (N = 0).

**Table 2.** Case Studies – DEC Configuration Matrix

| CASE STUDIES | A1 - REF | A2 | A3 | A4 | B1 | B2 | B3 | B4 | C1 | C2 | C3 | C4 | D1 | D2 | D3 | D4 | E1 | E2 | E3 | E4 |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 | 9 | 10 | 11 | 12 | 13 | 14 | 15 | 16 | 17 | 18 | 19 | 20 |
| nPV [-] | 0 | 250 | 500 | 1000 | 0 | 250 | 500 | 1000 | 0 | 250 | 500 | 1000 | 0 | 250 | 500 | 1000 | 0 | 250 | 500 | 1000 |
| nAC/CH [-] | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 |
| BATT [kWh] | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 2000 | 2000 | 2000 | 2000 | 20000 | 20000 | 20000 | 20000 |
| nHP [-] | 0 | 0 | 0 | 0 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 |
| nBOf [-] | 1 | 1 | 1 | 1 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| nSTH [-] | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 500 | 500 | 500 | 500 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |

**Table 3.** Case Studies – DEC Assumption for the Optimization

| **Parameter** | **Value** | **Unit of Measure** |
|---|---|---|
| *Fuel* (Price, LHV) | (1.00, 50.0) | (Euro/kg, MJ/kg) |
| *Electricity tariff* (Buy/Sell) | Refer to Figure A.3 | Euro/kWh |
| *PV* (Peak Capacity, Surface, Efficiency) | (550, 2.584,21.1) | (Wp, $m^2$, %) |
| *STH* (Surface, Efficiency) | (2.0, 40.0) | ($m^2$, %) |
| *COP (HP, VCCH, ABCH)* | (2.6, 5.5, 0.7) | (-) |
| *Battery (*RTE, $SOC_M$, $SOC_m$*)* | (93, 95, 5) | (%) |
| *Carbon Tax* | 80.0 | Euro/Ton |
| *DEC Emission Factor* | 0.212 | $kgCO_2$/kWh electric |
| *Natural gas Emission Factor* | 0.192 | $kgCO_2$/kWh fuel |

For the battery component instead, it is assumed that it can serve the entire DEC and so introduced with the nominal capacity, expressed in kWh.

On top of these 20 case studies (A1 – E4), the authors have also investigated three policy scenario related to the qualifications in terms of CO2 carbon credit and financial gain of selling the excess of electricity generated by the DEC to the National grid. The results of the scenario analysis will be deeply presented in the result section, by differentiating the colours of the candle stick bars charts. Accordingly, the three scenarios are considering that the yearly exported electricity (kWh exp):

- Scenario 1 (Blue): allow CO2 Certificate Recognition and exported electricity is reward.
- Scenario 2 (Red): NOT allow CO2 Certificate Recognition and exported electricity is reward.
- Scenario 3 (Green): NOT allow CO2 Certificate Recognition and exported electricity is NOT reward.

Price of electricity bought and sold are 230 and 70 euro/MWh.

### 4.1 Assumptions

According to the DEC building specifications given in section 2, to the ambient condition given by MARRA Database, and to the yearly load profiles for electricity, cooling and hearting shown in figure 3, the main assumptions required for the calculations have been presented in table 3. Indeed, main components specification such as nominal capacity, surface of each module, efficiency, and performance indexes such the Coefficient of Performance (COP) are fundamental parameters to perform the optimization process thanks to DECAPLAN™ Digital Platform.

To perform the environmental techno-economic analysis, prices of electricity (sell and buy) and cost of the carbon tax are also needed. Accordingly, since it has been considered power can be imported (Pimp) and exported (Pexp) from and to the National grid, buy & sell prices are 230 and 70 euro/MWh, respectively. Furthermore, to assess the overall yearly production of pollutant emissions in terms of Ton of CO2/year from the DEC, the emission factors of the system and associated to the combustion of the natural gas into fuel fed boilers have also been included in the optimization and thus included in table 3.

Once boundary conditions and assumptions have been set, the authors have been able to run the optimization and the scenario analysis above-mentioned thanks to DECAPLAN™ Digital Platform. Accordingly, results of the optimization together with discussion and consideration are given in section 5.

## 5. RESULTS & DISCUSSION

In this section, the authors present the results of the environmental techno-economic optimisation carried out by the DECAPLAN™ Digital Platform, taking the different DEC configuration and scenarios into considering. The case study A1 (order number 1) is the reference case study and represent the scenario in which all the electricity is imported from the national grid, all the cooling load is satisfied by the generation of air conditioning from individual unit splitters and the heat load is supplied by the heat power generated through the Heat Pump. In this configuration, the yearly CO2 emitted by the DEC is of 732 Ton/year and the overall OPEX are of about 540,000 euro/year. These two numbers are very important because they become the benchmark/baseline to compare all the other case studies and scenarios. Looking at the same DEC configuration A4 equipped with 1000 Solar PV modules, it can be observed by the charts given in figures 5 and 6, that for the scenario 1, where the amount of kWh exported to the grid is accounted in the overall CO2 emission per year, the year CO2 emissions drop of 21% to 575 Ton/year and the yearly OPEX decreases of 22% to 420,000 euro/year. This trend is justified by the fact that the integration of the solely Solar PV in the DEC configuration does not modify the load allocation of the other loads, such as cooling and heating. When A4 configuration is instead compared among the three scenario 1, 2 and 3, it can be clearly be observed that cCO2 credit mechanism of the scenario 1, does not allow in case 2 and 3 to achieve the same CO2 emissions reduction. Indeed, in case 2 (and equivalently in case 3) the maximum CO2 reduction is of 57 Ton/year, corresponding to about -9% CO2 emission reduction. On the OPEX side instead, scenario 2 shows 427,000 euro/year and scenario 3 shows 452,000 euro/year. The evaluation of the scenario B4, where the generation from the NG fed Boiler is swap with the Heat Pump system, shows an interesting trend among CO2 and OPEX. Indeed, given the marginal cost of the electricity from the grid and of the fuel and the different emissions factors, the solution B4 reduces the CO2 emissions of 65% leading to a yearly emitted value of only 254 Ton/year, with a corresponding OPEX of 460,000 euro/year, that is anyway a saving of 14.8% in the OPEX of the DEC. The introduction of 500 Solar Thermal Collector for the generation of heating and cooling in case C4, keep the reduction of the CO2 emissions practically unchanged, up to 66%, corresponding to an absolute value of 249 Ton/year, and reduces the OPEX of 15.0%, leading to a yearly OPEX of 457,000 euro. The scenarios D4 and E4 are characterized of the introduction of 2000 kWh and 20000 kWh battery capacity in the DEC. In the case of the smaller battery, D4, the CO2 emission reduction is of 64.5%, while the OPEX reduction is of up to 28%, corresponding to a yearly operating cost of 385,600 euro. In case of the large battery instead, E4, the CO2 emissions reduction is 64.0 %, while the OPEX reduction is up to 33.2%, corresponding to a 359,000 euro/year DEC operating cost. The reason behind the massive reduction on the OPEX due to the integration of the battery in the design of the DEC is because it allows to perform the peak shaving procedure and allow to reduce the dependency of the DEC from the National Grid. On the CO2 emissions perspective instead, the fact that each charging/discharging operation is characterized by a loss (round trip efficiency) leads to increase the demand of electricity (energy) in the DEC and consequently to a marginal increase of the CO2 emitted, in comparison between the case without battery. It is worthy of note, that the reduction is anyway very considerable and for sure – the OPEX cost massive reduction will justify the solution. An important consideration related to the introduction of the battery system into the layout are related to the fact that the exported power – in the case of 20000 kWh capacity – is almost zero along the entire year. This is an important consideration since grid complexity and regulation would rather prefer the DEC to be independent from the grid to ensure stability on the frequency of the electricity generated by the DEC system.

Indeed, by comparing the charts given in figures 7 and 8, that represents configurations D4 and E4, it is possible to observe how the capacity of the battery influences different aspects. The red chart representing the power imported from the National grid allows to understand how the dependency from the Nation Grid is much lower in case E4. Looking at the summer period, the DEC is fully independent from the National Grid and furthermore, the electric work exported to the grid is practically zero for the entire year. On the battery duty cycle operations, the grey chart in figures 7 and 8, it can be observed that the case D4 equipped with the smaller capacity, the battery system is adopted in day-to-day operations, accounting for supplying the DEC in case of intermittency of RES in the short term. When the capacity of the battery increases up to 20000 kWh, the storage solution become and interesting tool for planning long term operations, for ensuring flexibility and grid independence of the DEC system.

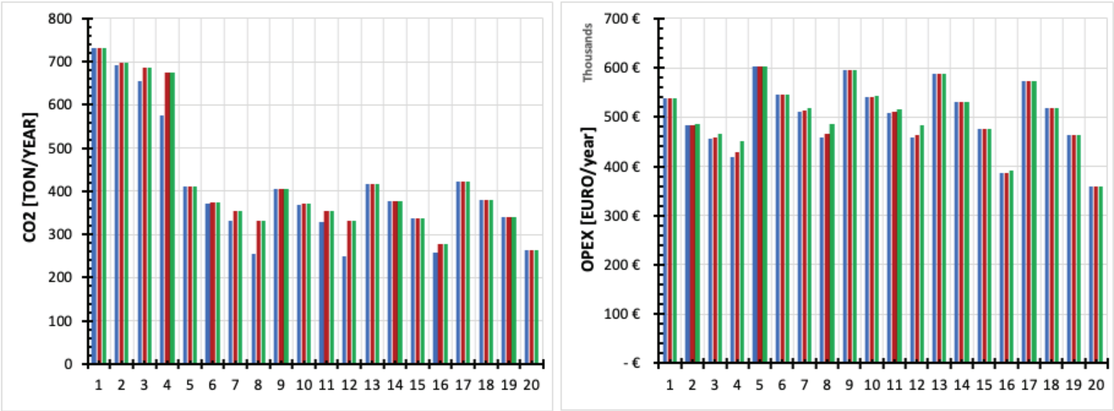

**Figure 6.** CO2 and OPEX comparison among (A1 – E4) configuration and Scenarios 1,2 and 3

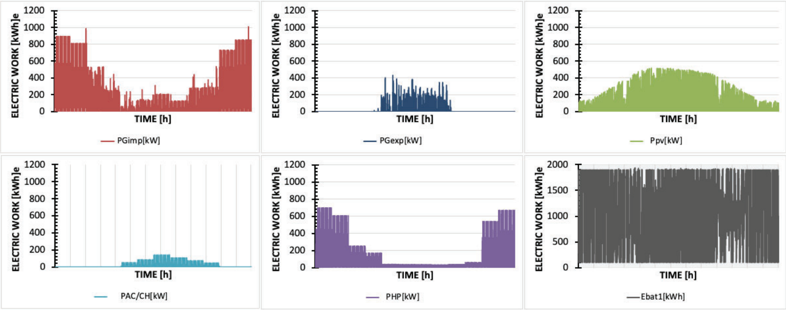

**Figure 7.** Configuration D4 – Dispatching Profile on the electric load.

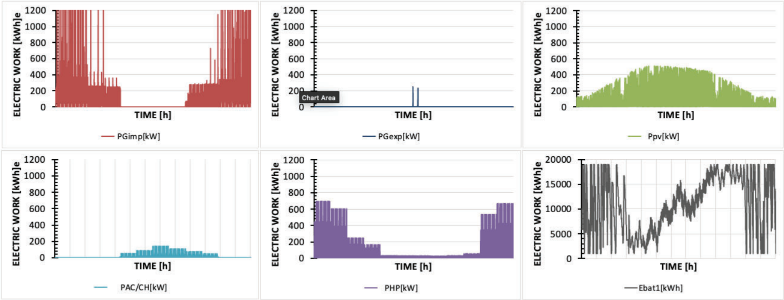

**Figure 8.** Configuration DE – Dispatching Profile on the electric load.

## 6. CONLCUSIONS

The paper investigated the promising topic of Renewable Distributed Energy Communities and their role in achieving environmental techno-economic alternatives in the pathway towards decarbonization. The concurrent requirements from the DEC users of electricity, cooling and heating make the design of optimal DEC a complex process, since multitude of variables are involved in the optimization process. The authors have developed a digital platform – DECAPLAN™- that can solve Master-Planning and Optimal Dispatch Problems of highly integrated DEC. Thanks to the modular approach proposed and to the optimization algorithm the authors have ranked the best DEC configurations in terms of potential in CO2 emissions and OPEX reduction. It has been demonstrated that an optimal designed DEC with Solar PV, Heat Pumps and Solar Thermal Collectors is capable to reduce of up to 65.1% the CO2 emissions yearly, when compared to the case in which all the assets are generated via fossil fuel sources (boilers and import from national grid). Indeed, the CO2 Emissions drop from 732.6 Ton/year to just 249.5 Ton/year, reducing the environmental impact of the DEC and reducing the cost associated to the carbon tax (savings of almost 40,000 euro per year of CO2 Tax). The maximum saving from the OPEX perspective – instead – takes place when the DEC is equipped with a large capacity electrochemical energy storage system, with capacity ranging between 2,000 and 20,000 kWh). Indeed, the CO2 reduction comparted to reference case is still very high – with 64% reduction, corresponding to 259.4 Ton/year, but the OPEX drop from 537,000 euro/year to about 385,000 euro/year, that leads to about 28.2% savings yearly, in the case of the 2,000 kWh battery. The authors decided to consider at the day of today the smaller battery as the most easy-to-implement solution for DEC since a much larger battery of 20,000 kWh would also imply to account for thermal management problems and surely much higher CAPEX. It is worth of note, that the larger energy storage capacity simulated in the paper as an electrochemical energy storage system, could also be simulated by alternative storage solutions and plant configurations, based on Hydrogen solutions.

For concluding, the authors have not considered the impact of the CAPEX in the optimal design of the system and for sure it will be the next brick the authors will integrated in the analysis for fully understanding and assessing the environmental techno-economic viability of DEC, in the holistic perspective, accounting for the entire lifetime of the DEC.

## Acknowledgments

The authors acknowledge and thank the Department of Industrial Engineering of University of Roma Tor Vergata and the Italian Ministry of University and Research (MUR) for the support.

**Nomenclature**

| | |
|---|---|
| $\mathrm{H}$ | Heating Power, W |
| $\mathrm{C}$ | Cooling Power, W |
| $P$ | Electric Power, W |
| $\dot{m}$ | mass flow rate, kg/s |
| $t$ | temperature, °C, timestep, h |
| $\eta$ | efficiency |
| $\delta$ | binary variable (0,1) |

**Subscripts and superscripts**

| | |
|---|---|
| $BO$ | Fuel Boiler |
| $PV$ | Photovoltaic |
| $STH$ | Solar Thermal Collector |
| $ABCH$ | Absorption Chiller |
| $AC/CH$ | Air Condition Unit / Chiller Unit |
| $HP$ | Heat Pumps |
| $BATT$ | Battery |

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