On the integration of the energy storage in smart grids: Technologies and applications

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Abstract
Smart grids are one of the major challenges of the energy sector for both the energy demand and energy supply in smart communities and cities. Grid connected energy storage systems are regarded as promising solutions for providing ancillary services to electricity networks and to play an important role in the development of smart grids. The aim of the present article is to analyze the role of storage systems in the development of smart grids. The article includes an analysis and a list of energy storage systems that are applied in smart grids. Various energy storage systems are examined ranging from electrical, electrochemical, thermal, and mechanical systems. Two case studies are presented that show the role of energy storage in effective management of energy demand and supply.

KEYWORDS
energy management, energy storage, power peak reduction, smart communities, smart grids

1 | INTRODUCTION

Smart grids are one of the major challenges of the energy sector for both the energy demand and energy supply of cities and communities.1,2 A transition from traditional electricity grids where energy is produced centrally and distributed to the various energy consumers is necessary to exploit distributed energy sources, energy loads, and storage components. Traditional grids lack flexibility in power generation and load operation, thus forming a semi-autonomous entity with limited energy management capabilities.3 Moreover, a smart micro-grid can operate connected to the main grid or in island mode.

Deployment of smart grids asks for innovative techniques for predicting and controlling electricity request to the grid, in order to reduce peaks, improve grid stability and optimize electricity costs.4 Smart grids can even contain millions of smart meters, which produce a huge amount of data about...
energy consumption. In addition to these time series data, additional correlated information about energy sources, weather, occupancy, building performance, and so on can be provided.5

The actions toward a fast implementation of the smart grid has increased recently due to policy and regulatory initiatives that promote smart grid reliability, integration of renewables, demand response, and energy storage.6,7

Energy storage is a critical component for smart grids.8–10 The significance of EES in energy networks is analyzed in Reference. 11 Optimal sizing and operation of storage systems provides peak power demand effective management, allows the maximization of renewables’ penetration, supports power quality and reduces energy networks’ expansion needs.12,13 Moreover the increased capital and operational costs to manage peak demands, the requirements for grid stability, resilience, and reliability have increased the interest of storage for grids.14

Typical energy storage systems for smart grids include15,16:

- Electrical energy storage, that is, electrostatic energy storage including capacitors, super capacitors, and magnetic/current energy storage.
- Mechanical energy storage such as flywheels, compressed air, and hydro-pump energy storage.
- Chemical energy storage such as electrochemical conventional batteries, fuel cells, solar fuels, metal-air batteries, and thermochemical reversible processes.
- Thermal (sensible, latent and thermochemical) energy storage.

Energy storage may also be provided through the control of building thermal storage17,18 and frequency control on loads.

The various categories of energy storage systems are depicted in Figure 1.

Various efforts have been performed to analyze the role of storage systems in the future development of smart grids and their interconnection in building, community, and city scale.19–22 The smart grids’ implementation, the zero energy and carbon communities’ targets, the distributed energy generation, and the increased penetration of renewables are mainly influenced by the successful integration of energy storage systems.23 The EES in power systems and utilities infrastructure stability and quality is also an important aspect and focus of research from various researchers.19

Another aspect of research includes the optimized operation of storage systems in smart grids. Examples of optimization methodologies for energy storage in smart grids are the Particle Swarm Optimization for scheduling the operation of various energy resources and electric vehicles (EVs)24,25 as well as the use of genetic algorithms and multi-objective optimization.8,26

The integration of storage in smart grids requires extensive research in analyzing performances for real case studies, setting key performance indicators, and benchmarking. To this end, the aim of the present article is to review the different research approaches on the actual implementation of storage systems when coupled with smart grids. The article starts with an analysis of the various energy storage systems and their performance when coupled with smart grids. Two case studies covering the actual implementation and results of electric and thermal energy storage are examined in Section 3 while Section 4 outlines conclusions and future prospects.

2 | ENERGY STORAGE SYSTEMS IN SMART GRIDS

2.1 | Electrical and electrochemical energy storage in smart grids

Electrical energy storage systems (EES) are very important for smart grids. Their role generally depends on the number

FIGURE 1  The energy storage systems categories
of charging-discharging cycles and the duration of their operation.\(^\text{16}\)

The benefits of electrical energy storage in grids are:

- **Time and peak shifting:** for power utilities generation cost can be reduced if energy is stored at off-peak hours and released during peak hours.
- **Power quality:** power utilities should supply power voltage and frequency within specific limits. EES can perform frequency regulation and this is done by adjusting supply to the changing demand.\(^\text{27,28}\) In isolated power grids, electrical storage systems support the power utility to provide stable power to the customers.
- **End-user peak shaving, load shifting, and dynamic pricing:** energy storage can be used by customers such as industrial users for peak shaving in order to minimize the part of their energy bill that varies according to their highest power demand. Such a service is very profitable if the peaks are sufficiently predictable and of relatively short duration.\(^\text{29–31}\)
- **Continuity of energy supply:** a storage device is able to substitute the network in case of interruption. EES are often used as an emergency power supply in case of outage.\(^\text{32}\)
- **Limitation of disturbances:** the storage can help customers to comply with commitments related to limited disturbances thus improving grids' resilience.\(^\text{6,33,34}\)
- **Compensation of the reactive power:** an electrical storage system, via the power electronics converter, is able to locally compensate for the reactive power.\(^\text{35,36}\)

Batteries are the first EES to be considered in smart grids. Battery systems can offer a number of high-value opportunities, provided that lower costs can be obtained. The most widely used batteries are lead acid nickel-cadmium, lithium, and sodium sulfur.\(^\text{37–39}\)

The main concerns for wide adoption of these batteries are the overall cost, the limited number of charging cycles (or lifetime), the depth of discharge, the low energy density, and the sustainability of the materials used.

On the other hand, flow batteries can be an alternative. For example, Vanadium redox flow batteries (VRFB) are a promising option to mitigate many of these shortcomings.\(^\text{40}\) A work performed by Lucas and Chondrogiannis\(^\text{27}\) demonstrated how a VRFB based storage device can provide frequency regulation and peak-shaving functions.

A review of sodium-sulfur batteries, redox-flow batteries, and lithium-ion batteries can be found in Reference.\(^\text{14}\)

Moving to another subcategory of electrical energy storage, ultra-capacitors are another emerging solution. Ultra-capacitors\(^\text{41}\):

- Have almost 20 times higher capacitance than normal capacitors.
- Have longer life cycle.
- Are insensitive to environmental variations of temperatures.
- The ultra capacitors can be applied for:
  - Optimized operation of renewable energy sources.\(^\text{42}\)
  - EVs power management.\(^\text{41}\)
  - Hybrid energy storage systems (HESS).\(^\text{43}\)

Superconducting magnetic energy storage (SMES) is an alternative for high density storage systems' requirements.\(^\text{44}\) In a case study for Malaga Spain, SMES are used to eliminate grid signal fluctuations created by industrial clients. The specific industrial clients incorporate three-phase induction motors that deteriorate the quality of the grid signal. Also hybrid configurations of SMES, for example, SMES with batteries, with fuel cells, and so on are very encouraging solutions.

Furthermore EVs are more and more considered as necessary technologies for energy storage in smart grids. EVs can operate in two different modes that can serve as an energy storage in a smart grid that is:

- **“Grid-to-Vehicle”** (G2V) operation where the vehicles are charged using electricity from an electric power grid.
- **Vehicle-to-Grid** (V2G) operation where vehicles are discharged to an electric power grid during the parking hours. Another approach is the integration and interconnection of EVs to specific buildings formulating the “Vehicle-to-Building” (V2B) alternative\(^\text{46}\) which allows buildings to become energy prosumers and increase the share of renewable resources.

Through these operational modes, EVs can act either as a load or as a decentralized energy storage in a smart grid.

The expansion of EVs includes significant challenges concerning grid stability. Smart bi-directional charging strategies as well as management strategies of EVs with RES have been proposed by various researchers.\(^\text{47–50}\) Accurate information regarding the state of the EVs connected to the electrical grid is required.

Examples of EVs case studies are tabulated in Table 1. More detailed implementation of EVs in various countries is included in Reference.\(^\text{51}\)

Combinations of the aforementioned technologies provide significant advantages. For example:

- The use of battery pack that are incorporated in EVs equipped with bi-directional charging systems is proposed by Reference.\(^\text{58}\) Commercially available lithium-ion batteries (C\(_6\)/LiNiCoAlO\(_2\) type) are used and a degradation model is developed and validated. This model is integrated
It is shown that the smart grid is able to extend the life of the EV battery. The EVs’ battery pack capacity fade is reduced by up to 9.1% and power fade by up to 12.1%.

HESS with high energy storage battery bank and ultracapacitor unit are proposed by Reference 59 to support the integration of PV in electricity grid. During load changing, first the ultra-capacitor group is discharged and then the battery group supplies the load. Thus, battery life is preserved by reducing deep-discharge rate.

Integration of (a) flywheels; (b) plug-in electric vehicles (PEVs); and (c) price responsive thermal loads is presented in Reference. 17 The storage is used for the day ahead Markey using dynamic management systems and revenue obtained by energy storage over a duration of one day, in $/MW, is used as a basis of comparison between different storage technologies. 60

### 2.2 Mechanical energy storage in smart grids

Concerning mechanical systems energy storage is well established in the form of either large scale hydro-pumped systems (HPS) but also medium and smaller scale systems. 8 Various examples show the performance of HPS in smart grids. For example:

- **HESS**

| Table 1 Electric vehicles case studies |
|---------------------------------------|
| **Case study** | **Characteristics** | **Main results** |
| Electric buses, Guwahati city, Assam, India. | A high capacity energy storage device is used between the grid and the transportation system. A solar plant is introduced to curtail the system dependence on the grid. | Reduction of internal combustion engine vehicles and improved air quality. Electrification of transportation with support from renewable energy. Transformation of transportation. |
| Application of electric vehicles (EVs) at the Caribbean island of Barbados | Peak electricity demand 167.5 MW and 240 MW installed generation. An 10 MW utility-scale solar Photovoltaics (PV) and 20 MW of distributed solar PV on residential and commercial rooftops. The EVs are considered either as static demand or as smart charging with V2G capability. | Decrease of grid-connected storage up to a 13% if EVs are charging during the day. V2G allows increased penetration of renewables and reduces the investment needs in grid-connected storage for 12% in case of EV night charging and to a 20% for day charging. |
| São Miguel Island, Azores, Portugal | Medium voltage distribution network is analyzed. A transformer is utilized which supplies one private industry client via a 250 kVA, 10 kV/0.4 kV oil-immersed transformer. An EV charging scheduler is analyzed. | With 60% EV penetration the loss of life of the transformer is reduced by a range of 7.54% at 60% EV penetration to 76% at 100% EV penetration. With the EV charging scheduler a 98% of loss of life reduction is achieved. |
| Tenerife, Spain | Data from the cars, mobility and power demand have been taken into account to analyze the EVs penetration. | Considering various levels of penetration to the grid, EVs are utilized as storage systems that allow to significantly reduce the amplitude difference between valleys and peaks of the electric energy demands curve and thereby to contribute to the efficient management of smart grids. |
| Korcula, Croatia | Analysis of 100% renewable energy sources (solar and wind) in combination with 100% share of vehicles is performed | The import and export peak loads have not been affected by the smart charge share reduction of EVs. |
| UCLA campus city of Santa Monica | UCLA Smart Grid Energy Research Center (SMERC) is used as a testbed. Two stages optimization is performed: (a) to reveal the optimal EV load profile for the day-ahead energy market; (b) to control all online EVs in the system to follow the optimal load profile and charging scheme generated by stage (a). EV users’ patterns is analyzed to optimize the EVs operation and couple it with a demand response program. | A 18% energy cost reduction is achieved while lowering the computational cost of the control system. |
generation by the PV, the water is pumped to the upper reservoir. During peak hours or lower PV generation water flow from the upper reservoir to lower through turbine/generator to produce electricity and supply the power to loads. The HPS includes a turbine unit and a motor. A variable speed doubly fed induction machine is considered.

- The incorporation of HPS in Sardinia is discussed by Reference. 62 Sardinia has on the one hand limited interconnections with the mainland and on the other hand has high solar and wind energy resources' potential. In the specific island the power system can be seen as a microgrid. HPS is used for load balancing. During off-peak hours, power is utilized to run the pumps, whereas during on-peak hours the stored water is released through turbines to produce electric power. This increases the renewable energy production penetration.

- A residential settlement is exploiting PV with pico-hydro turbines and HPS to minimize the energy cost in a dynamic pricing electricity system. 64 During periods that energy price is low, the energy produced by the PV is stored as gravitational energy to the pump storage and is used by the pico-hydro turbines when energy price is high. A case study in Tiruchirappalli, India is analyzed.

In addition, compressed air energy storage (CAES) can be considered as one storage technology that has a very high ESOL index. An ESOL index is the total amount of energy stored over the lifetime of a storage technology unit, divided by the amount of energy used in producing that unit. 65 An example of using CAES is described by Reference. 66 In this research CAES is combined with wind energy conversion system to provide distributed energy resource and storage to microgrid in order to minimize its dependence on the transmission line in case of the microgrid’s expansion. This integration can significantly decrease the demand on the transmission line while simultaneously reduces the community's energy cost by 18%. Moreover CAES can moderate fluctuations of renewable energy production due to the large-scale storage capacities, high ramp rate, and quick start-up time and therefore are an attractive technology for smart grids. 67

Although CAES is a mature and attractive technology for grid energy storage systems there are shortcomings that need to be considered. The CAES efficiency is much lower than similar technologies such as HPS, attributed to the fact that during compression, thermal energy is wasted. Thermal energy storage coupled with CAES is proposed to overcome the aforementioned issue. 68 In this framework, the thermal energy produced in the compression stage is stored in a TES unit for its subsequent deployment during the expansion stage, realizing an Adiabatic-CAES plant with an efficiency that is reaching almost 70%-90% depending on the configuration. 69 Another CAES application shows that the specific energy storage system can balance fluctuations in power generation and frequencies instabilities. An air flow controller is utilized designed to control the air flow from the CAES system, so that the microgrid follows the various load demands to maintain a stable frequency. 70

Some examples of mechanical storage systems utilized in grid applications are tabulated in Table 2.

### 2.3 Thermal energy storage in smart grids

Thermal energy storage is divided to sensible, latent, and thermochemical energy storage as depicted in Figure 1. An overview of thermal energy storage systems (TES) is provided by Alva et al. 76

Sensible heat energy is stored by changing the temperature of the storage materials. The amount of stored energy depends upon the medium’s density, specific heat, volume, and temperature variation. 77 Sensible storage can be stored in solid (stones, salt), liquid (molten salts, water, thermal oil) as well as liquid with solid filler (water with pebbles, molten salt with oil, and so on). 78 Water is one of the commonly used material for heat storage in residential application while water tanks and aquifer storage systems are the most commonly used water-based storage systems. Other materials used for sensible energy storage are depicted in Figure 2.

Concerning sensible thermal storage systems, heat pumps can be an indicative example seen as part of the demand side that can be actively managed to support the realization of a smart grid. 79 When heat pumps are utilized in conjunction with thermal storage, they offer the possibility to decouple electricity consumption from heat demand. This is very useful in increasing the performance and renewables penetration in a smart grid.

Molten salts are the most commonly used storage material in concentrated solar power (CSP) applications due to the thermal properties and cost (see Table 3). 80 An example of molten salts thermal storage coupled with CSP is analyzed in Section 3.2.

Latent thermal energy is stored by changing the phase of the storage materials. The latent storage applications usually exploit the phase change between solid and liquid phases to store/release thermal energy, due to the higher heat storage capacity per volume and low volume difference between these two phases. 6 The main advantage of latent vs sensible storage is the higher storage capacity.
per unit of mass (and volume), resulting in lower space requirements.\(^1\) Also, as phase change occurs, there is only a small temperature difference during the charging or discharging process.

Phase change materials (PCMs) are becoming more and more attractive over the last years for space heating and cooling in buildings, solar applications, off-peak energy storage, and heat exchanger improvements.\(^2\)–\(^4\) PCMs are

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**TABLE 2**  
Case studies of mechanical energy storage

| Case study                                      | Characteristics                                                                 | Main results                                                                                   | Ref  |
|------------------------------------------------|--------------------------------------------------------------------------------|-----------------------------------------------------------------------------------------------|------|
| Flywheel sizing study for homes Austin, Texas  | A flywheel energy storage sizing study is performed using home energy data for 741 homes at Mueller Development Community in Austin. The energy data include home energy consumption and solar photovoltaics (PV) generation. 25% of homes have a 6 kW PV. The trade-offs between energy storage capacity and power requirements are assessed in home, transformer, and community level. | In community level diurnal energy storage requires 1200 kW flywheels while for power smoothing 300 kW are sufficient. The peak power in the power smoothing configuration is reduced by 8% for the whole community. kW | 71   |
| CAES application in Clemson University, South Carolina | A solar assisted microgrid is developed using PVs 15 kW. Compressed air energy storage is utilized to supply a MicroTurbine and facilitate its operation. | The average power generation on a daily basis by the PV panels runs a 5.2 kW CAES for 5 hours storing 1108 kg of air at a 1.2 MPa pressure. This corresponds to 8.1% efficiency improvement in energy generated by the system with CAES compared to conventional production. | 72   |
| Integration of hydro-pumped systems (HPS) in Sardinia | Sardinian power system is simulated under the hypothesis of considering a base-load of 1200 MW, and taking into account the variability of PV and PV energy production. Sardinia is connected to the Italian mainland with a high voltage direct current (HVDC) connection called SAPEI, which allows 1000 MW import/export with the mainland. HPS is utilized to provide additional load at times of high RES generation and low electricity demand, enabling further RES peak capacity and/or regulating the export through HVDC connections. | HPS is used when the production overcomes the SAPEI limit of 1000 MW, and this is done for 395 hours per year. Also the released energy stored from the HPS helps to reach the 1000 MW. | 62   |
| HPS of Alps as the battery of Europe         | 14 HPS plants with 1380 MW capacity are installed in Switzerland. The estimated energy storage is 369GWh. In this research, the Switzerland’s HPS sector is studied in conjunction with the German electricity system by taking into account the intermittent operation of RES (solar, wind and mix). The overall system is assessed vs the loss of load probability (LOLP) and the energy shortages. | The German electricity system becomes more stable when the storage plants are added to the German electricity System. The loss of load probability is considerably reduced for all three RES scenarios (solar, wind and mix). Moreover, there is a drop in energy shortages and energy surpluses. Energy surpluses are stored to the HPS and this allows for a production increase, that is, lowering the shortages. | 73   |
| Adele project, Sachsen-Anhalt, Germany       | 260 MW plant with CAES storage                                                                                                                                       | Discharge time of CAES is equal to 5 hours and the efficiency is equal to 70%.                   | 74,75|
| Joint European Torus (JET) Fusion FES facility in Culham, Oxfordshire | Flywheel energy storage system of 400 MW capacity                                                                                                                   | Discharge time of around 30 seconds at rated power, resulting to 12 000 MJ stored energy. The plant is used for providing power balance services to the Culham Centre for Fusion Energy (CCFE). | 74,75|
substances that can exist in the solid, liquid or gaseous states depending on the temperature and pressure of the storage conditions. An example of using PCMs in district level for low temperature district heating is included in Reference81 showing that PCMs have better performance in district heating applications than sensible storage systems, that is, water purifiers. A significant drawback is the increased cost of the PCMs especially in specific temperatures.

The thermochemical energy storage has received a considerable attention the last decade.85 Long term thermal energy storage, for example, seasonal storage for solar thermal applications can increase the fraction of solar energy utilization factor from 20%-30% to 50% or even 100%. This can be achieved by thermochemical energy storage where the heat is stored in chemical bonds of special materials and the charging/discharging process is an endothermic or an exo-thermic reaction.86

Examples of integrating thermal storage in smart grids/microgrids are87:

- A low temperature solar power plant with temperatures between 80 and 130°C is coupled with Sofia-Antipolis smart grid designed in the framework of PREMIO project. This solar plant is also connected to a sensible heat water storage device of 150 kWh and a 5 kWc organic Rankine cycle (ORC) turbine. The water storage device is utilised to provide energy even when there is no energy production from the solar plant.88

- Underground aquifer thermal energy storage systems (ATES) able to cover the energy demand of group of buildings is analysed in Reference.89 This storage system can be applied as seasonal storage system in moderate climatic conditions where there is shortage of heat during winter and an excess during summer. The ATES therefore can be considered as a heat source or sink, or a storage for thermal energy depending on the season and the needs.

- Sensible thermal storage can be provided by the building envelope in the form of thermal mass and/or insulation. Typical new residential buildings in Belgium equipped with air-to-water heat pumps that supply either radiators or a floor heating system are considered in Reference.90 The analysis is based on the energy cost reduced as well as on loads' flexibility. The flexibility of the loads is quantified by the amount of load volumes shifted. By formulating the buildings in a smart grid typology and by applying smart grid control strategies, a reduction of 13% of energy costs by the consumer is reached. The flexibility is increased by 3% to 14% with the same thermal comfort.

- An activated building wall, PCM, hot water tank and a thermochemical material (TCM) storage are investigated to optimize the scheduling of thermal storage and minimize the

| TABLE 3 | Advantages and disadvantages of concentrated solar power (CSP) technologies |
|---|---|
| Design | Line focus technologies | Point focus technologies |
| Technology maturity | Parabolic trough | Solar tower |
| Preferred scale | Most mature | Commercial deployments |
| Operating cost | High | Low |
| Capital Cost | High | Low |
| Technology required | High | Low |
| Annual solar to Net electricity conversion efficiency (if connected to a power block) | High | High |
| Characteristics | Thermal storage | Technology maturity |
| Thermal Storage | Feasible | High temperature |
| Characteristics | Thermal efficiency | High temperature heat transfer fluid possible |
| Thermal Storage | Thermal efficiency | High temperature heat transfer fluid possible |

KOLOKOTSA ET AL.
The cost reduction is estimated to be equal to 12.5%.91

The grid of the University of Genoa is used to optimize the combination of renewables and thermal storage in order to cover the thermal loads on yearly basis by minimizing capital and variable costs. The grid consists of 100 kWe micro gas turbine, 20 kWe internal combustion engine for electricity and hot water, a 100 kWe adsorption chiller for cooling. The grid is also equipped with a small size wind turbine and photovoltaic solar panels. The optimized sizing of renewables indicates a 17 kW PV installation and a 3 kW wind turbine. The sizing of renewables indicate that the optimum size of thermal storage to be equal to 30 m³.92

Ice storage is used to provide cold water to the business district of Paris La Defense through a distribution network linked with a central refrigeration system of three units with a unit capacity of 8 MW. The storage is performed daily with a charge temperature at −7°C and discharge temperature 4.5°C. The ice storage capacity is equal to 240 MW with an efficiency of 95%.87

3 | ENERGY STORAGE AND SMART GRIDS: CASE STUDIES

3.1 | Case study 1: the leaf community smart grid energy storage system

3.1.1 | General description

The case study is the micro-grid of the Leaf Community, in Angeli di Rosora, Italy, (Figure 3). The energy production sources connected to the grid are a micro-hydropower plant, of 48 kWp, four rooftop PV installations of total 488.6 kWp, a vertical PV of 10.7 kWp and a dual axis Solar Tracker of 18 kWp. The Leaf Community consists of five buildings, which are interconnected with the energy production technologies mentioned above. Moreover, EVs are used for the transportation of the Leaf Community employees. The Leaf Community is equipped with:

- An electrical storage system of 224 kWh.
- A thermal storage system with heat capacity of 1883.7 MJ/K.

All the previously mentioned power loads, renewables and storage components are in parallel to one single point of delivery (POD). All smart grid components are monitored and controlled via a web-based monitoring platform.

3.1.2 | Leaf community web-based monitoring and control platform

The Leaf Community's smart grid is controlled by a centralized software called energy management system (EMS). The EMS is organized into three levels as depicted in Figure 4. This architecture allows a reliable, efficient, and flexible control of a heterogeneous cyber-physical system.

| Leaf Lab HVAC Units—Model type | Heating power (kW) | Heating COP | Cooling power (kW) | Cooling EER |
|-------------------------------|-------------------|-------------|-------------------|------------|
| NECS-WN/S 0412               | 130               | 4.8         | 159.2             | 6.89       |
| NECS-WN/S 0904               | 286.9             | 4.19        | 239.3             | 6.19       |
| NECS-WN/S 0904               | 286.9             | 4.19        | 239.3             | 6.19       |
Local control
Each microgrid element is equipped with a local control composed by a PLC and an embedded PC. The PLC reads the data and executes the real time operational functions necessary for the proper functioning of the plant. The PC allows the plant control with a local human machine interface (HMI). The communication between central and local control is realized by REST Web Services.93

Central control
The facility operator uses a centralized software to monitor the smart grid and to execute several control logics in order to optimize the energy fluxes.

The central control reads all real time data from each local control PC. Information is organized in logical representations of a physical asset (PV plant, Micro-Hydropower plant, Electrical Storage) characterized by properties and behaviors.
The software combines behaviors, data from the grid and forecast data in order to implement the control logics and, moreover, it sends commands to distributed energy resources.

Examples of control for the storage are:

- Peak shaving: it cuts the power consumption peaks.
- Self-consumption: it maximizes the amount of energy self-consumed.
- Max export/max import: the target is maximizing the energy produced/consumed by leaf community.

Data analysis

The central control sends data to a central platform information. This platform stores long term data and provides validation and reconstruction algorithms.

The facility operator can visualize historical and real-time data via a web browser in order to define KPIs and analyze the grid’s performance.

3.1.3 | The TES of the leaf community

The TES is a water tank with dimensions 12.3 m x 11 m x 3.4 m and a capacity of 400 m³ (Figure 5).

The water tank is buried and insulated with 16 cm of extruded polystyrene and is used to store the sensible heat for the energy demand of the connected buildings.

TES was initially used to implement load shifting, by charging the TES during the night, when the energy cost is 10% less than daytime, and discharging it during the day. This usage was not considered efficient due to the fact that the TES losses are higher than the energy cost reduction during night. The thermal energy losses are calculated equal to 12% form the water tank due to conduction. An extra 25% is lost by the GSHPs due to the fact that in order to charge and discharge the thermal storage, it is necessary to increase and decrease the GSHP output temperature set-point during winter and summer respectively. Therefore, the surplus power produced by renewables is considered the most cost-effective solution. The energy buying price for RES is 70% higher than the selling price to encourage self-consumption strategies. The Leaf Microgrid has a surplus production of energy only during weekends and holidays. A performance analysis of the TES is included in Section 3.1.5.

3.1.4 | Electrical energy storage

The EES consists of Lithium 220 kW/kWh (Figure 6). The specific energy storage system is used for optimization of the energy flows and peak shaving. Its optimized operation is described in Reference. 94 When the charging-discharging of the batteries is optimized based on their swing range and life cost, while energy demand and production for the Leaf Community is predicted using artificial neural networks, a 6% reduction of the energy cost is achieved. A performance analysis is included in Section 3.

3.1.5 | Performance analysis of energy storage for the leaf community microgrid

Performance analysis of the TES

The TES is mainly exploited to reduce the peak power of the Leaf Community's interconnected buildings.

One of the buildings' energy demand that is covered by TES is the Leaf Lab. Leaf Lab is a 6000 m² building equipped with ground source heat pumps (GSHPs), chilled beams, and fan coils. The Leaf Lab heating, ventilation, and air conditioning system's (HVAC) specifications are tabulated in Table 4.

The excess energy produced by the Leaf Community's energy production sources during weekends, holidays, and so on is used to operate the heat pumps and store heating or...
cooling energy in the thermal tank. The stored energy is then used to optimize the HVAC efficiency and reduce peak demand during working hours. The overall operation is described below:

1. The thermal storage is charged during weekends using the excess production of leaf community.
2. This excess production is used to operate GSHP2 and GSHP3. The charging process begins when there is a PV power production that exceeds 60 kW. This is the threshold for the GSHP3 activation.
3. After the activation of the GSHP3 and if there is an excess of 50 kW, GSHP2 is activated.

The activation of the heat pumps for charging the thermal storage is allowed only during weekends from 8:00 AM to 16:00 PM in winter and from 7:00 AM to 18:00 PM in summer. The pumps are switched off at the end of each schedule or if the PV production is significantly reduced over a specific time period. In case the PV power is instantly reduced, power is withdrawn from the grid in order to keep the heat pumps under operable mode.

For the deactivation of the heat pumps, if the power from the grid is greater than 130 kW, GSHP3 is switched off. Then, if the energy withdrawn from the utility grid exceeds 90 kW, the GSHP2 is switched off.

The TES charging status and temperature is depicted in Figure 7.

TES performs better during spring and autumn because the outdoor air temperature is close to the indoor temperature set-point and the HVAC system is not stressed. The thermal energy, stored during the weekend can support the HVAC needs for the whole week. Figure 8 depicts typical TES power exchange with the grid during a spring week. Positive values represent the charge of storage on Saturday and Sunday, while negative values represent the discharge during the week days. During summer and winter, TES is sufficient for 1 or 2 days depending on the outdoor weather conditions. TES covers almost 25% of the Leaf Lab building’s energy demand.

Performance analysis of the BES
The BES is used either for peak shaving or for self-consumption. Peak shaving depends upon the maximum electricity power peak measured by the Leaf Microgrid POD and is almost 610 kW. Since the nominal power of EES is 220 kW the EES is activated when the electricity power is higher than 450 kW.

The peak shaving mechanism operates in the following way:

- If the microgrid consumes more than 450 kW the electric energy storage is activated in order to keep the energy consumption under the specific threshold.
- If the microgrid consumes less than 150 kW, then the electric storage is recharged.

The peak shaving operation is depicted in Figure 9. Each time the POD power exceeds 450 kW the battery is discharged to support the extra power requirements. Also during night that the microgrid’s energy demand is reduced, the batteries are charged.

Sometimes the EES energy capacity is not enough to guarantee the performance over time. In Figure 10, the POD power, SOC of battery and power of battery are depicted. When SOC is 30% EES is not activated which is the case on 22 November after 16:00. This means that EES nominal power should be increased to cover more effectively peak shaving demands.

Self-consumption strategy targets to maximize the self-consumed energy. The Leaf Microgrid is discharging power to the grid only during weekend. A branch of 116.65 kW photovoltaic plant and a little building called Ramo Leaf Farm with 30 kW peak consumption is formulated. The EMS is configured to perform a guaranteed daily energy exchange between the BES and the branch. This means that the energy stored in BES is self-consumed by the branch. The self-consumption strategy showed that Ramo Leaf Farm consumption in the 2018 is reduced by 33% compared to 2017 due to the maximization of the PV plant energy self-consumption as depicted in Figure 11.

3.2 | Energy storage of CSP and integration with smart grids

3.2.1 | Technical description of a polygenerative solar plant
The technology described in this section is developed and tested by IDEA Srl. The solar plant consists of a compact...
collector for multi-generative applications which is based on a Linear Fresnel concentration system. The solar rays are reflected to the same target by means of appropriate mirrors that constantly track the solar position during the day. The collector has been optimized to reduce the space required for its installation thanks to a compact and lightweight design and a reduced focal length.

The solar collector is able to concentrate the solar radiation onto a receiver tube in which a high temperature HTF is heated. The thermal energy is collected at about 270°C and is stored inside a storage tank. This stored energy can be utilized either by absorption chillers for cooling or directly by heating infrastructure.

Additionally, with the concentrated solar energy, solar heat is converted into power by running thermodynamic cycles. Thus, the system can produce electricity through an ORC unit. The schematic of the polygenerative plant is depicted in Figure 12.

3.2.2 | The polygenerative solar plant in a university campus

The polygenerative solar plant described in section 3.2.1 has been installed in the Campus of the University of Palermo, Italy as part of the University's Solar Living Lab. It consists of three strings with seven modules each, for a total collecting surface of about 480 m² as depicted in Figure 13. All parts of the installation are described in the following sections.
The design parameters of the solar plant are tabulated in Table 5. The monthly solar energy produced by the LFR is tabulated in Table 6.

The primary optic of each of the 21 modules is composed by 18 curved mirrors, 32 cm wide and 400 cm long, with a total reflectance of about 95%. Reflective panes are fixed on a steel structure that is connected to the tracking system. Mirrors with different curvatures are installed from the center to the extremity of the module in order to modulate the focal length according to the respective position of the absorber tube placed at about 3.5 m above the module plane.

The secondary optic is made by a metal mirror with a solar reflectance of about 84%. It has been appropriately designed with a compound parabolic collector (CPC) configuration in order to refocus on the absorber tubes the imperfectly collimated solar rays. The absorbers are steel pipes with cermet coating, vacuum glazed. The peak thermal power of the solar field is 220 kWth with an estimated annual thermal energy production of 295 MWhth. The HTF is a synthetic oil with a specific heat coefficient of 2 kJ/(kgK) and a maximum outlet temperature of 310°C. When selecting oil as a transfer fluid, the main limiting factor, to be taken into account for the maintenance of stability, is the maximum temperature of the oil, as, above this temperature, decomposition, and rapid chemical degradation occurs.
The advantages of hot oil utilization in the Fresnel system (solar energy generating systems, SEGS) compared to water utilization as direct steam generation (DSG) are\textsuperscript{98,99} the following:

- With the synthetic oil possible instability due to two-phase flow of water/steam in the collector is avoided. Moreover, possible process instability due to large changes in fluid volume during boiling is minimized.
- If superheated steam is generated in the collector, there is a risk of thermal stress.
- High temperature wet and/or dry conditions with DSG require higher-grade materials.

Nevertheless, the oil as HTF implies the following disadvantages:

- There is an increased risk for fire and pollution.
The upper temperature limit of ~300 to 400°C required for the use of synthetic oil should be continuously monitored. There is a need to replace almost 5% of the oil each year. Antifreezing is also needed when temperature is below 14°C.

The upper temperature limit imposed by the stability range of the oil directly implies an upper limit for the temperatures in the ORC.

### 3.2.3 Short-term thermal energy storage—The buffer tank

When the heated oil exits the absorber tube, the HTF enters a short-term buffer storage of 800 L (see Figure 12) as the effective specific heat of the HTF increases. This first buffer serves for stabilizing the exchange processes within the LFR. The integration of a buffer storage capacity simplifies the control of the power plant and allows an extended reaction time for backup systems, which are intended to compensate longer periods of reduced insolation. This short-term storage is important for damping fluctuations in power.

| FIGURE 13 | The layout of the installation site at IDEA srl. (Long 38.10o Lat 13.34o). The three strings cover an installation of total 480 m² |

| TABLE 5 | Fresnel parameters used for the efficiency calculation |
| Outer absorber tube diameter (m) | 0.07 |
| External diameter of glass cover (m) | 0.125 |
| Receiver coating absorbance (%) | 0.958 |
| Glass cover transmittance (%) | 0.964 |
| Glass mirrors width (m) | 0.32 |
| Primary optic reflectance | 0.958 |
| Secondary optic reflectance | 0.84 |
| Module length (m) | 4 |
| Number of mirrors per row | 18 |
| Module focal length (m) | 3.5 |
| Total number of modules | 21 |

| TABLE 6 | Monthly solar thermal energy, efficiency, and thermal power of IDEA's linear Fresnel reflectors (LFR) system |
| Month | Solar energy reaching the mirrors surface (kWh) | LFR solar thermal energy gain (kWh) | Monthly average efficiency (%) | Thermal peak power (KW) |
|--------|---------------------------------|---------------------------------|-----------------------------|-------------------------|
| January | 40 527                          | 3215                           | 8%                          | 63.56                   |
| February | 42 064                          | 6040                           | 14%                         | 87.85                   |
| March   | 60 381                          | 16 429                         | 27%                         | 153.64                  |
| April   | 73 345                          | 27 106                         | 37%                         | 189.14                  |
| May     | 104 554                         | 45 443                         | 43%                         | 199.12                  |
| June    | 112 330                         | 49 264                         | 44%                         | 220.60                  |
| July    | 133 208                         | 58 950                         | 44%                         | 221.39                  |
| August  | 106 128                         | 44 547                         | 42%                         | 191.31                  |
| September | 77 963                        | 24 436                         | 31%                         | 169.66                  |
| October | 64 843                          | 12 225                         | 19%                         | 127.89                  |
| November | 55 120                         | 5375                           | 10%                         | 70.57                   |
| December | 43 923                         | 2881                           | 7%                          | 47.61                   |
| Total   | 295 911                         |                                 |                             |                         |
output associated with short-term disturbances such as passing clouds. The short-term thermal storage mechanism uses a pressurized vessel and a simple, inexpensive storage medium. In the specific LFR system, pressurized N₂ is used at 3 bars. Storage is limited to small capacities in the order of some hours.¹⁰¹

3.2.4 | The molten salts thermoclinic storage

The heated oil from the receiver tube, after exiting the first short term buffer, is diverted to a heat exchanger to heat a TES fluid, typically a Molten Salt (MS) mixture. MS-TES systems are generally built with two separated tanks (cold tank at 290°C and hot tank at 380°C when oil is used as heat transfer fluid).

Unfortunately, molten-salts freeze at relatively high temperatures 120°C to 220°C. This means that special care must be taken to ensure that the salt does not freeze in the solar field piping during the night. Newer linear Fresnel designs may allow use of higher-temperature molten salts.¹⁰¹

An innovative and simplified solution has been adopted in the polygenerative solar plant installed in Palermo. A particular ternary mixture of nitrate salts with a low melting temperature is used in a single stainless steel thermal tank with a diameter of 1.8 m and a height of 3.5 m. It contains 8 m³ of salt as well as equipment such as sensors, electric resistances and heat exchangers.

A eutectic mixture of CaCO₃/NaNO₃/KNO₃ (42/15/42% w) is heated by the heat transfer fluid from the solar field in the tank. This particular salts’ mixture with a melting point of 130°C (and a maximum temperature of about 450°C)
allows both an easy operation and maintenance. The natural stratification of the heat into the thermal storage (thermocline effect) allows the charging and discharging process in the same storage using the natural temperature gradient difference. Two different heat exchangers are installed, respectively, the discharging heat exchanger with a power of 150 kW at the top and the charging heat exchanger with a power of 200 kW at the bottom of the tank (Figure 14).

During the day, the hot oil coming from the solar field heats the molten salts transferring the thermal energy gained by the collectors to the storage.

The molten salts thermal storage is equipped with two heat exchangers specifically designed with coils in AISI 316 stainless steel. The exchangers are respectively connected to the oil buffer tank, for the TES charging, and to the equipment (absorption chiller and ORC turbine) for the TES discharging. Both heat exchangers are helicoidally shaped and designed for an optimized heat exchange process between the oil flow and the molten salt mixture zone, either during the charging or the discharging phase. Two vertical channels of 7.62 cm (3 in.) diameter, directly connected to each heat exchanger, allow the salts transport to the top and to the bottom, during the charging and the discharging phases, respectively.

A total storage of 400 kWhₘₜ is achieved with 16 tons of hydrated salts, capable of driving a small double effect chiller (23 kWₑ—COP 1) and a small ORC (10 kWₑ with a net efficiency of 10%) described in the next sections.

The thermal distribution into the tank is monitored by a group of 20 sensors (PT100) immersed with a mutual inter-distance of 15 cm into the salt mixture. An extra set of four temperature sensors measure the thermal profile close to the charging heat exchanger in order to evaluate any thermal difference into their layer. Figure 15 shows the distribution of the temperature into the thermal storage, recorded in a typical operating day during the months of July to June 2018.

The operational tests are conducted with the only contribution of the solar energy produced by LFR collectors at different inner temperature profiles. Tests have confirmed, also at this scale, the effective production of a thermocline effect during the charging phase, with a natural stratification of the temperatures from the top to the bottom and a constant thermal power exchange during the whole process. The exchange of thermal power is calculated by the inlet and outlet oil temperature to the TES and the values of specific heat and density. The natural stratification of the MS bulk temperature is recorded by T19-T1 sensors, while the heat stored in the upper volume less influences the sensor T20, which is placed close to the shell in the bottom zone.

Thermal energy stored into the tank is used to provide thermal energy after sunset or during cloudy periods. When the storage is fully charged, it is by-passed and the solar field drives directly the equipment for cooling or power generation.

The thermocline single tank approach could overcome the traditional “two molten salt thermal tanks” design, usually adopted in the CSP solar fields.

New applications of binary and ternary mixtures, with a lower melting point, have been discussed from a technical and economic perspective. The target of these applications is to compare the efficiency of single tank thermocline molten salts storages and commercial “two tank” configurations.102 In such studies, thermocline storages systems with nitrates salts, used in the range of 300 to 400°C with quartzite fillers, have been considered economically advantaged due to the reduced costs of salts, materials, and equipment.103 Nevertheless, some flexibility in the design is required for the adoption of a single tank approach, as the two tanks configurations represents the most suitable solution to keep the plant working close to the design point.104

The innovative MS-TES installed in Palermo is designed for an operative range of 200 to 300°C, able to drive equipment operating in a flexible range of 160 to 200°C. The aim is to investigate the application of medium temperature thermocline storage in civil and industrial solar energy plants. The benefits of a new generation of cheaper and simple thermal batteries could be also valuable in recovering of wasted thermal energy from many industrial processes.

3.2.5 | The absorption chiller

An absorption chiller is integrated in the solar field in order to serve the cooling loads of the offices during the summer season. Thermally driven chillers, using solar energy, are a good alternative compared to conventional electricity driven chillers to meet the growing air-conditioning demand and to cut electrical peak loads during the summer. Also, their use
allows to save primary energy and to reduce greenhouse gas emissions associated with the electricity generation from fossil fuels. Solar thermal cooling systems have been widely used and particularly absorption cooling systems. Solar cooling using single-effect water-LiBr has been studied since the mid 1970s and until now, many studies have been conducted to improve their efficiency and performance.

FIGURE 17 Organic Rankine cycle (ORC) section of the pilot plant in Palermo

FIGURE 18 Steady-state calculation of daily solar thermal energy gain and linear Fresnel reflectors (LFR) efficiency

FIGURE 19 Thermal energy in the solar field with a safety overheating temperature set at 230°C
performed. In literature, applications of various configurations have been reported such as:

- Flat plate collectors and single-effect chillers
- Evacuated tube collectors and single-effect chillers
- Compound parabolic collectors (CPC) and single-effect chillers
- Parabolic trough collectors (PTC) and single-effect chiller
- Parabolic trough collectors and double effect chillers and systems
- Linear Fresnel collectors (LFC) and double-effect chillers

While single-effect absorption chillers work at relatively low driving temperatures (between 80°C and 95°C) produced by efficient flat plate or vacuum tube collectors and delivering low COPs (between 0.55 and 0.75), double-effect absorption chillers demand a higher driving temperature (up to 160°C) which results in higher overall efficiency (COP = 1).

IDEA’s community and solar field is equipped with a Li/Br double effect absorption chiller with a heating capacity of 23 kW at a thermal COP of about 1.1. The chiller, driven by oil is heated at 195°C and the outlet temperature is 165°C. It is integrated with a cooling tower, which keeps the cooled water from 7 to 12°C.

3.2.6 | The ORC system

The ORC generator installed at the IDEA’s community in Palermo has a net electric power output of 10 kW. The basic concept of its operation is shown in Figure 16 and the operational characteristics of the ORC are depicted in Figure 17. The heat transfer fluid passes its thermal energy to the high temperature working fluid vapor in the evaporator. The high temperature fluid vapor enters turbine and produces mechanical work for electricity generation. The turbine exhaust steam is condensed in the condenser and pumped again to the evaporator for recirculation. The ORC cycle working fluid main characteristics are thermal stability, toxicity, flammability, and cost. As an example, toluene has good technical characteristics regarding stability, temperature range and high energy density but condenses at sub-atmospheric pressures. The n-pentane on the other hand operates at super-atmospheric pressures over a wide range of condensing conditions.

Several fluids could be exploited in the ORC generation process, and the suitability of each alternative option depends on following aspects:

- The location of the power plant. If it is located near a populated or environmentally sensitive area, more flammable, and toxic fluids might be excluded and less hazardous mediums are preferred.
- The environmental aspects, that is, the fluid global warming potential.
- The cost of the fluid. The best performing fluid might not be the one with the lowest procurement cost.

The ORC generator installed in Palermo uses a heavy fluid R245fa that allows to raise the inlet temperature up to 210°C and the outlet oil temperature at 165°C. An external cooling tower of 90 kWth is connected in order to discard the waste heat.

3.2.7 | Performance analysis of the energy storage of the CSP

Quasi dynamic state calculation of LFR energy production

A detailed hourly steady-state model is developed using TRNSYS, taking into consideration the climatic data, the geographic location of the installation site, as well as the optical characteristics of the solar thermal plant. The thermal model is based on the international standard ISO 9806.
Taking into account the solar radiation and ambient temperatures from the nearest weather data site in the University of Palermo and a temperature difference of $T_{in} = 270^\circ C$ and $T_{out} = 250^\circ C$ with an optical efficiency of 0.64, the monthly thermal energy output is calculated as shown in Figure 18. The results show an annual LFR energy production of 295 MWh (Table 5).

**Monitoring of the solar field**

The solar field is monitored by a SCADA system connected to all the sensors distributed in the circuit in order to control and manage the main working parameters. Figure 19 shows the registered temperatures and thermal power of the LFCs installed in Palermo during the test of 21 June. The average temperature of the HTF (ie, Paratherm NF) between the inlet and outlet of the absorber tubes of the three rows is represented in red. The direct radiation on the normal plane is in blue and measured in W/m$^2$. The total power gained by the solar field during the test is represented in orange.

During the test, the solar field produces about 550 kWh$_{th}$ (considering the thermal losses of distribution) in almost 4 hours. The thermal power reaches a peak greater than 170 kW$_{th}$, with a thermal efficiency of 45%, corresponding to an optical peak efficiency of about 50%. This value is acceptable considering the reduced reflectance of mirrors and transmittance of the borosilicate glass of the absorber tubes due to the dust. Safety systems, implemented in the solar field, verify the set point temperatures achievements. When set points are reached the defocusing of mirrors is activated as depicted in Figure 20.

Figure 21 shows the performance of LFR while TES is in charging phase. The average HTF temperature is increased to reach the predefined set point. Then, when the oil is pumped from the buffer to the charging heat exchanger, thermal power is generated as highlighted in Figure 20 and a peak is created and the HTF temperature remains constant due to the energy transfer from the solar field to the thermal storage. The solar field has produced, at the described operative conditions, 880 kW$_{th}$ of which 550 kW$_{th}$ are produced during the thermal charging phase of the molten salts.

![Figure 21](image1.png) **FIGURE 21** Thermocline effect measured by specific thermal sensors (PT100) distributed in the vertical axis of the thermal storage

![Figure 22](image2.png) **FIGURE 22** Electric power produced by rank organic rankine cycle (ORC) by thermal energy stored into the thermal energy storage system (TES)
The thermal energy transferred to the storage system produces a thermocline effect even at low-temperature thermal profiles. Figure 21 shows the thermocline stratification produced by oil pumped at 200°C into the TES with molten salts at about 160°C. During the test, the temperature profiles, measured at different heights by the sensors from 1 (top) to 20 (bottom), are respectively increased at the temperature values of the upper zone.

The thermal energy stored is used both for driving the Chiller and the ORC. Above a threshold of 210°C in the discharging heat exchanger zone, the thermal energy can be transferred to the generator of the ORC. For example, with a charging heat exchanger zone, the thermal energy can be transferred to the generator of the ORC. Above a threshold of 210°C in the discharging heat exchanger zone, the thermal energy can be transferred to the generator of the ORC. For example, with an oil flow of 3.2 m³/hour and an inlet temperature of 176.2°C and outlet 159.7°C the ORC has a power of 8.8 kWe. Under these conditions the evaporative tower is fed with 7 m³/hour of water at 34.6°C cooled to the ORC at 30.1°C (Figure 22).

4 | CONCLUSIONS AND FUTURE PROSPECTS

Smart grids are expanded in districts, communities, and cities in order to meet reduction of energy requirements and achieve sustainable and resilient energy supply. In this smart grids’ era energy storage systems have a major and critical role for both the energy supply and the demand side. Peak power shaving, load shifting, demand response, and dynamic pricing can be effectively supported with the appropriate and careful selection of energy storage. Electrical and electrochemical energy storage technologies are the first choices when considering smart grids. EVs technology is steadily enhanced, tending to become one of the dominant solutions for smart communities and smart cities. On the other hand, batteries are expected to be significantly upgraded while advanced control systems and devices can ensure that batteries’ life reaches its maximum.

Although emphasis is put in the electricity supply and demand and its coverage by renewable energy systems, polygeneration and thermal energy storage are equally important for sustainable and resilient energy systems. Significant research effort is put toward advanced thermal energy storage systems with increased capacity and efficiency. Ground source heat pumps, intelligent materials with improved thermal properties are continuously developed and integrated in community and city level.

Smart, resilient cities of the future should be able to adapt to new conditions and thrive, rather than merely survive. In the roadmap toward resilience, polygeneration and “polystorage” will ensure security of supply and high quality of energy services.

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