Energy storage systems review and case study in the residential sector

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Abstract. Energy storage is recognized as an increasingly important parameter in the electricity and energy systems, allowing the generation flexibility and therefore the demand side management. It can contribute to optimal use of generation and grid assets, and support emissions reductions in various economic sectors. Energy storage can support the European Union (EU) targets for efficient use of energy by helping to ensure energy security, a well-functioning internal energy market, and successful implementation of more carbon-cutting renewables online. By strengthen the use of energy storage, the EU can decrease its energy imports, improve the efficiency of the energy system, and keep prices low by better integrating variable renewable energy sources. Moreover energy storage can contribute to better use of renewable energy sources in the energy system since it can store energy produced when the conditions for renewable energy are appropriate but demand may be low. In this framework, primary objective of this study is the investigation, the comparative analysis and the evaluation according to specific criteria of the current thermal energy storage systems. Electrical, electrochemical, thermal, mechanical and chemical energy storage technology and systems are extensively presented and categorized in terms of their advantages and disadvantages as well as in terms of their technical and financial characteristics. This paper also presents the implementation of thermal energy storage in the residential sector. More specifically is examining the application of a phase change material storage system into the building’s walls cavity. The study focuses on the contribution of the applied energy storage system to the overall increase of the energy efficiency of the building.
Abbreviations
CAES: Compressed air energy storage
CESS: Chemical energy storage system
ECC: Electrochemical capacitor
ECESS: Electrochemical energy storage system
EESS: Electric energy storage system
ESS: Energy storage system
EU: European Union
FB: Flow battery
FC: Fuel cell
FES: Flywheel energy storage
EERB: Energy efficiency regulation of buildings
LAB: Lead acid battery
LB: Lithium battery
LHSS: Latent heat storage system
MESS: Mechanical energy storage system
NASB: Sodium - sulphur battery
NB: Nickel battery
PCM: Phase change material
PHES: Pumped hydro energy storage
RES: Renewable energy source
RESHS: Renewable energy source harvesting systems
SHSS: Sensible heat storage system
SMES: Superconducting magnetic energy storage
TCESS: Thermo chemical energy storage system
TESS: Thermal energy storage system

1. Introduction The global electric energy consumption; according to International Energy Agency (IEA), has increased from 14781 billion kWh in 2003 to 21699 in 2015. The major part of this energy comes from the burning of fossil fuels and as a result the CO$_2$ emissions have been increased as well [1]. Due to negative environmental impact and limitation of fossil fuels, the need of harvesting RES appears. RES considered being: solar; wind; thermal; tidal; hydro kinetic, hydro dynamic, geothermal, ocean and biomass energy [2]. The RESHS transform the freely supplied energy to useful forms of energy. Their main disadvantage is that they cannot supply energy constantly to the demand [3]. The development of RESHS decreases the CO$_2$ emission and creates a great interest in the development of ESSs [4]. ESSs store excess energy, for a later use during energy shortage periods. Energy can be stored in five different forms thus electrical, electrochemical, thermal, mechanical and chemical [2,4]. The operation of an ESS includes 3 main stages: a) energy supply to the system charging stage b) storage of energy to the system storage stage c) subtraction of energy from the system discharging stage [5]. Currently the most efficient method to store energy is through hydro pumped and latent heat energy storage [2].
2. Electric energy storage systems EESS are being categorized to electrostatic and magnetic systems. The capacitor and the ECC are electrostatic systems while the SMESS is a magnetic system [2].

2.1. Capacitor: The capacitor is composed by two conducting plates positioned very close to each other [2,6]. The energy capacity of a capacitor depends on the size of its plates; bigger plates mean more energy storage. Its capacity also depends on the distance between the two conducting plates. The distance between the plates is filled with a non-conducting material called dielectric [2,6]. The dielectric material affects the capacity of the capacitor as well [5].

2.2. Electrochemical capacitor: The difference between a capacitor and an ECC is the ability of the later to store more energy [2]. ECC is also known as electric double layer capacitor. Based on oxidation - reduction reaction, that takes place on its internal high reversibility plates, an ECC store electric energy [7]. ECC’s solid conductors are immersed in an electrolyte solution; the storage of electric energy happens by means of that [2]. During charging electrolyte’s ions are clinging on the ECC’s conductors. The layer of attached ions on the surface of the conductors and the conductor’s ions create two parallel layers of ions; the name of double layer capacitor stems from that phenomenon [7].

2.3. Superconducting magnetic energy storage: SMESS is composed of three main parts: a superconducting coil; a power conditioning system and a cryogenically cooled refrigerator [1,4]. The energy is stored in the magnetic field; created by the flow of direct current through the coil; the coil’s temperature must be below its superconducting critical temperature [2,4]. The coil is extremely sensitive to temperature’s changes; as a result energy storage is only feasible while the cryogenically cooling refrigerator is operating [4]. The stored energy is released with the discharge of the superconducting coil [2].

In Table 1 the advantages and disadvantages of EESS and their use in RES systems are given in tabular form.

![Figure 1. Superconducting magnetic energy storage [2].](image)

Table 1. Advantages – Disadvantages of EESS and their use in RES systems.

| EESS     | Advantages                     | Disadvantages      | Use in RES systems |
|----------|--------------------------------|--------------------|--------------------|
| Capacitor| Energy storage for very short periods | Small capacity      | No use             |
| ECC      | High charge-discharge efficiency (95%) | Low voltage        | Wind parks         |
| SMESS    | High number of charge-discharge cycles | Expensive to run   | Wind parks         |

Table 2. Technical and financial characteristics of EESS.

| EESS     | Capacity (MW) | Lifetime (years) | Capital cost (€/kWh) |
|----------|---------------|------------------|-----------------------|
| Capacitor| 0.05          | 5                | 897                   |
| ECC      | 0.3           | 20               | 1795                  |
| SMESS    | 0.1 – 10      | 20               | 8974                  |
3. **Electrochemical energy storage systems** ECESS transform chemical energy to electrical energy and vice versa [2]. Battery uses a chemical reaction to transform the stored chemical energy to electric energy [1]. The stored electric energy creates voltage on the battery’s terminals [2]. A battery consists of one or multiple cells, connected in series or in parallel. Each cell consists four main parts: an anode or negative electrode, a cathode or positive electrode, an electrolyte and a separator between the anode and cathode for electric insulation [5]. Batteries are categorized, according their operation, to: primary cells, secondary cells, reverse cells batteries and FC [2]. ECESS are Lead acid; Nickel; Sodium - Sulphur and Lithium batteries. FB and FC are also considered to be ECESS.

In Table 2 the advantages and disadvantages of ECESS and their use in RES systems are given in tabular form.

| ECESS  | Advantages                        | Disadvantages              | Use in RES systems     |
|--------|----------------------------------|----------------------------|------------------------|
| LAB    | High efficiency                  | Small lifetime             | Wind parks, PV         |
| NB     | Fast charging                    | High self discharge        | Wind parks, PV         |
| NASB   | No maintenance                   | High manufacturing cost    | Wind parks             |
| LB     | Limited environmental effect      | Danger of overcharging     | Wind parks             |
| FB     | Small self discharge             | Complicated equipment to run| Wind parks             |
| FC     | Zero emissions                   | High manufacturing cost    | No use                 |

**Table 3.** Advantages – Disadvantages of ECESS and their use in RES systems.

| ECESS | Capacity (MW) | Lifetime (years) | Capital cost (€/kWh) |
|-------|---------------|-----------------|----------------------|
| LAB   | 0 – 40        | 5 – 15          | 359                  |
| NB    | 0 – 40        | 10 – 20         | 718 – 1346           |
| NASB  | 0.05 – 8      | 10 – 15         | 270 – 449            |
| LB    | 0.1           | 5 – 15          | 2243                 |
| FB    | 0.3 – 15      | 5 – 15          | 135 – 897            |
| FC    | 0 – 50        | 5 – 15          | 9 – 18               |

**4. Thermal energy storage systems** TESS are being used for heating and cooling of buildings; on electric energy production plants and in various industrial applications [1]. TESS can be categorized...
by the material of their storage medium; to: sensible heat; latent heat and thermo chemical heat ESS [1,2,4,5,8,9].

4.1. Sensible heat storage systems: SHSS are the least expensive and simplest TESS. Their operation is based on heating and cooling of their liquid storage or solid storage medium [4]. The thermal energy is stored in the medium by the increase of its temperature; without changing its initial phase [1]. The amount of the stored energy is proportional to the specific heat capacity, the mass of the material used and the temperature change during charging – discharging cycle [1,5,8]. The most commonly used material for SHSS is water [1,4,9]. Other liquids used as storage mediums are molten salts and thermal oils [1,2]. Solid storage mediums used in SHSS are stones; concrete; metal; marble; granite and dirt [1,2,4,5]. When a solid medium is used as a storage medium; an additional thermal liquid is used as heat transfer medium; these types of SHSS are called solid base system [5]. Storage efficiency of SHESS starts at 50% and can be as high as 90% [4,9]. A SHSS is composed by a storage medium; a storage tank and input/output devices [1,5].

4.2. PCM: During charging and discharging of a LHSS the used storage medium is changing its phase; the materials used as storage medium are called PCM [5]. The heat is stored or released during the medium’s phase change; while the material is absorbing or releasing energy [1]. The medium’s temperature during its phase change is constant [1,8]. The phase change can be solid to liquid; solid to solid; liquid to gas and vice versa. The processes reverse during charging and discharging [1,5,8]. The most common phase change is from solid to liquid [5]. During charging the material’s temperature increases while the material absorbs heat until its melting point. At that point the material’s temperature stops increasing and the material starts to change its phase, while it still absorbs heat. Charging and discharging of a LHSS depends on the melting and solidification of the PCM used [1]. PCM are divided in organic and inorganic materials. Organic PCM are those made of paraffin, fatty acid, esters, alcohols, glycols and eutectics. While salt hydrates, nitrate salts, carbonate salts, chlorine salts, sulfate salts, fluorine salts, hydroxides, metal, alloys and salt eutectics are considered inorganic PCM [8]. H$_2$O is the most commonly used PCM for solid to liquid phase change [1]. Solid to solid phase change offer less specific latent heat but it is easier to use that liquids; because it does not require a storage capsule. Liquid to gas phase change offers higher specific latent heat; but because of the enormous volumetric difference between phases is not often used. The thermal energy storing capacity of a PCM is the multiplication of its mass by its specific latent heat [8]. Storage efficiency of a LHSS varies between 75% and 90% [4]. LHSS’s energy capacity is four times greater than of a SHSS; capacity of LHSS can reach 100 kWh/m$^3$ while of SHSS 25 kWh/m$^3$ [4,9]. Important technical characteristics for a PCM, used in LHSS, are its thermal conductivity; density and enthalpy during phase change. Those characteristics determinate PCM’s volumetric heat capacity [2].

4.3. Thermo chemical energy storage systems: Thermal energy in TCESS is stored indirectly [2]. TCESS operating temperature is between 200$^\circ$C and 400$^\circ$C [8]. In a TCESS reversible physico-chemical reactions are taking place; these reactions are identified as the charging and the discharging of the system [1,2,4,5,8]. Absorption and adsorption of energy; are an example of these reactions during which the system get charged and discharged [2,8]. While charging a thermo chemical material C absorbs energy and gets divided to two separate materials A and B. This physico-chemical reaction is endothermic one. During discharging the materials A and B form initial material C and as a result the stored heat is released. This physico-chemical reaction is exothermic [2,5,10]. Storage efficiency of TCESS starts from 75% and it can reach 99%. TCESS has greater energy capacity than SHSS and LHSS. The stored energy can reach 300 kW/m$^3$ [4]. Also TCESS has high thermal density which can reach 1000 MJ/m$^3$ [1,2,8]. In addition they are capable to store energy for long periods with very low energy losses [1,8]. The material A and B are stored separately in room temperature without going through further physico-chemical reactions; as a result there is no self-discharging [1].
In Table 3 the advantages and disadvantages of TESS and their use in RES systems are given in tabular form.

**Table 5. Advantages – Disadvantages of TESS and their use in RES systems.**

| TESS  | Advantages                               | Disadvantages                        | Use in RES system         |
|-------|------------------------------------------|--------------------------------------|---------------------------|
| SHSS  | No toxic or expensive materials used     | Small energy density                 | Solar panels, geothermal  |
| LHSS  | High energy density                      | Differentiation of PCM’s volume per cycle | Solar panels, geothermal, PV |
| TCESS | High efficiency and energy density       | High manufacturing cost              | No use                    |

**Figure 4.** Working principles of a TCESS [5].

**Table 6.** Technical and financial characteristics of TESS.

| TESS | Capacity (MW) | Lifetime (years) | Capital cost (€/kWh) |
|------|---------------|-----------------|----------------------|
| SHSS | 0.001 – 1     | 10 – 30         | 0.1 – 10             |
| LHSS | 0.001 – 1     | 10 – 30         | 10 – 50              |
| TCESS| 0.01 – 1      | 10 – 30         | 8 – 100              |

5. **Mechanical energy storage systems** MESS stored mechanical energy; either as kinetic energy or as dynamic energy. Their main advantage is their fast and direct release of their stored mechanical energy [2]. MESS are considered to be PHES; CAES and FES [2,4].

5.1. **Pump hydro energy storage:** PHES stored energy by pumping water from a low tank to a high tank; the low tank is altitude wise lower than the high one [2,5]. Beside the two tanks a PHES includes an electric motor; which can be used as a pump while charging or as a power generator while discharging [4]. The quantity of the stored energy is proportional to the altitude difference between the two tanks and also the quantity of stored water [5]. Storage efficiency of PHES varies between 65% and 85% [1,5].

5.2. **Compressed air energy storage:** Operation of CAES is based on compressing air using inexpensive energy; produced on low energy demand periods; and its later release onto a turbine for the operation of an electric power generator [4,5]. The first CAES started operating in 1978 in Huntorf; Germany (290 MW). It was followed by the McIntoch CAES plant in Alabama (110 MW) in 1991. These two are the only operating CAES worldwide [1,5,11]. A CAES is consisted by a
compressor; a storage tank and a turbine. The turbines used in CAES for power generating are based on Brayton’s thermodynamic cycle [2]. The operation of a CAES is similar to the one of a common turbine [1]. During charging the generator operates as a motor supplying power to the air compressor. During discharging the compressed air is inserted in the combustion chamber and then is released on the turbine. The turbine is responsible for moving the electric power generator [5]. Although CAES produce CO\(_2\) they are capable of supplying three times more electric power to the grid than a common turbine for power generator; while consuming the same among of fuel [1].

5.3. Flywheel energy storage: The kinetic energy is stored in a FES by increasing the revolutions per minute of a flywheel [1,2,4,5]. Flywheels can be attached to an electric power generator; which results in transforming kinetic energy to electric [2,4]. The energy capacity of a flywheel is proportional to its mass and the square of its speed. The capacity of a FES varies depending on the durability of the flywheel’s material [5]. The main determination factors of the energy density of a FES are the flywheel’s geometry and material [1]. FES Storage efficiency is approximately 90% [5]. Flywheels are categorized as low rpm flywheels and high rpm flywheels [1,2,5]. Low rpm flywheels are consider those who reach less than 6000 rpm. High rpm flywheels can reach \(10^5\) rpm [5].

In Table 4 the advantages and disadvantages of MESS and their use in RES systems are given in tabular form.

| MESS   | Advantages              | Disadvantages          | Use in RES systems       |
|--------|-------------------------|------------------------|--------------------------|
| PHES   | Quick respond time      | High construction cost | Wind parks, hydro electrics |
| CAES   | Limited self discharge  | CO\(_2\) emissions     | Wind parks, hydro electrics |
| FES    | Low maintenance cost    | High self discharging  | Wind parks               |

Table 7. Advantages – Disadvantages of MESS and their use in RES systems.

Table 8. Technical and financial characteristics of MESS.

| MESS   | Capacity (MW) | Lifetime (years) | Capital cost (€/kWh) |
|--------|---------------|------------------|----------------------|
| PHES   | 100 – 5000    | 40 – 60          | 4.5 – 90             |
| CAES   | 3 – 400       | 20 – 60          | 1.8 – 90             |
| FES    | 0.25          | 15               | 4487                 |

6. Chemical energy storage systems Chemical energy is stored in the chemical bonds between atoms and molecules. During chemical reactions the stored chemical energy is released. During the energy release the old chemical bonds break and new ones are formed. That results in the change of the material’s composition. Chemical fuels are globally the number one energy source. Coal, gasoline, petroleum, natural gas and liquefied petroleum gas are the most commonly known ones [2]. The currently used chemical fuels produce big quantities of CO\(_2\) emissions. CESS is under constant observation because it can replace the chemical fuels used and help in decreasing CO\(_2\) emissions [1]. CESS mainly focuses on hydrogen and synthetic natural gas storage systems [1,2]. Biofuels are also considered as CESS [2].

7. Case study of TESS application in the residential sector In the framework of the presented research work the application of a TESS system in the residential sector in order to evaluate the appropriate TESS it is examined. The chosen TESS is considered to be positioned in the walls’ cavity of a commercial apartment. Initially, a typical apartment was selected and its constructional details and factors were determined. Then, a calculation of its thermal losses was carried out, according to the attached literature. After, the TESS selection, that of LHSS, the PCM used in the LHSS was selected
to be capable of storing the apartment’s thermal losses. Finally, the required PCM amount and the placement of its cases were determined.

7.1. Selected Building: The selected building constitutes a typical Greek apartments’ building. Its structural characteristics and efficiency factors were determined from the EERB [12]. The area’s climate characteristics are determined from the Hellenic National Meteorological Service [13]. The building is located in Nea Makri in Attica region. Nea Makri is included in Greek climatic zone B. The building is newly built. The building is elevated from the ground and has a terrace on the roof. Additional factors essential for calculating its thermal losses were considered [14]. Determination of outside temperature is very important in calculating a building’s thermal losses, the outside temperature of Nea Makri during wintertime; according to the EERB meteorological stations of Attica; was set at 5.4° C. While during summertime was set at 29.4° C. The inside temperature of the apartment was set to 20° C.

![Figure 5. Apartment’s top view [15].](image)

7.2. Apartment’s heat losses: A study for the calculation of the apartment’s thermal losses was carried out [15]. Main steps in calculating the thermal losses of a surface are the measurement of surface, the determination of the surface’s thermal conductance and the temperature difference between the divided, by the surface, areas. The upright surfaces, on which thermal losses are appeared, are marked in figure 5. The aggregation of the engravings’ factor and the apartments’ use factor is important. For this application the thermal losses both during the summertime and the wintertime were calculated.

| Room         | Wintertime | Summertime |
|--------------|------------|------------|
| Bedroom      | 20.8       | 13.4       |
| Living room  | 20.8       | 13.4       |
| Kitchen      | 9.7        | 6.2        |
| Hall         | 13.3       | 11.1       |
| WC           | 12.2       | 9.2        |
| In total     | 76.7       | 53.2       |
Table 9 shows the thermal energy losses. Table 10 is an example of the excel sheets used to calculate the apartment’s heat losses. This case study is only supported by a theoretical calculation of the thermal losses of an apartment. Therefore it doesn’t represent the actual thermal loads of the apartment during its everyday use. The apartment is considered to be heated during a day for 12 hours.

Table 9. Thermal energy losses.

![Table 9](image)

Table 10. Calculation of wintertime thermal losses of bedroom.

| Surface | Orientation | Surface thickness (cm) | Length (m) | Height (m) | Surface Area (m²) | Openings (m²) | Area (m²) | U factor (W/m²K) | Temperature difference (K) | Thermal losses (W) | Orientation factor (%) | Heating duration factor (%) | Total surface factor (%) | Total thermal losses Qs (W) |
|---------|-------------|------------------------|------------|------------|-------------------|---------------|-----------|------------------|--------------------------|----------------------|------------------------|--------------------------|--------------------------|--------------------------|
| C       | nw          | 30                     | 3.4        | 9.5        | 3.8               | 5.7           | 0.5       | 15               | 38                       | 5                    | 20                     | 1,25                     | 47                       | 481                     |
| F       | op          | 1.8                    | 2.1        | 3.8        | 3.8               | 2.3           | 15        | 127              | 5                        | 20                   | 1,25                   | 159                      | 2                        | 8                       | 1                        | 1                        | 1                        | 1                        | 89                       |

Total thermal losses (W) 481

7.3. Selection of the appropriate TESS: The suggested TESS is a passive LHSS. Main parameters for this selection are that operates at low temperatures and that has a daily charging-discharging cycle. The main compartment of a LHSS is the PCM. The used PCM must be able to absorb thermal loads and also to fit accordingly with the temperatures of the application. The LHSS is placed in the walls cavity in an effort to reduce thermal losses and not for the elimination of the heat losses [16,17,18].

Table 11. PCM manufactures.

| Company name | Website               | Product | Specific heat capacity (kJ/kgK) |
|--------------|-----------------------|---------|--------------------------------|
| Rubitherm Technologies GmbH | www.rubitherm.eu | RT 25 | 170 |
| Environmental Process Systems Ltd | www.epsltd.co.uk | A25 | 150 |
| Climator | www.pcmproducts.net | ClimSel | 140 |
| www.climator.com | | | |

Table 12. Technical details of RT25.

| Material | Melting temperature (°C) | Solidify temperature (°C) | Specific heat capacity (kJ/kgK) | Density (kg/l) | Volume expansion (%) | Cost (€/kg) |
|----------|--------------------------|---------------------------|--------------------------------|---------------|---------------------|------------|
| RT 25   | 22-26 (25)               | 26-22 (25)                | 170                            | 0.88 (S)      | 14                  | 5.3        |
The suggested PCM for this application is the RT25 of Rubitherm Technologies GmbH due to its high thermal capacity (source: www.Rubitherm.eu). RT 25 stores and releases its thermal energy at almost constant temperatures. RT 25 is placed in aluminum cases that are manufactured by the same company. The case’s dimensions are 450 x 300 mm² and thickness of 10 or 15 mm. The cases contain ½ or 1 kg of RT 25. The preferred position to place the PCM cases is close to the inside surface of the wall [16,17,18]. The aluminum cases of RT 25 in this application are placed under the plaster. The dimensions of the aluminum cases are 450 x 300 x 10 mm and each contains ½ kg RT 25.

Table 13. Technical details of RT 25 placement.

| Structural element | Surface (m²) | Number of cases | Quantity RT 25 (kg) | Cost RT 25 (£) |
|--------------------|--------------|-----------------|--------------------|---------------|
| Ceiling            | 49           | 362             | 181                | 959.3         |
| Floor              | 49           | 362             | 181                | 959.3         |
| T1*                | 11.4         | 84              | 42                 | 222.6         |
| T2*                | 8.6          | 63              | 31.5               | 166.9         |
| E*                 | 6.8          | 50              | 25                 | 132.5         |
| Total              | 124.8        | 921             | 460.5              | 2440.6        |

*as shown in figure 5.

7.4. TESS application discussion: The purpose of this study was to evaluate a TESS capable to store the thermal losses of a commercial apartment. The selected TESS stores thermal loads while using a PCM. For the purpose of the study was necessary to calculate the thermal losses of the apartment. This case study is not supported by a dynamic simulation. The selected PCM was selected according to calculated thermal losses and the desired apartment’s temperature. For that the PCM had to be able to carry the whole amount of the thermal losses. The required amount of PCM depends on the thermal losses and defines the sizes of the aluminum cases. Given data were the structural characteristics of the building, the outside temperature and the desired inside temperature. The main parameter was the PCM type. The overall thermal losses of the apartment were calculated at 76.7 MJ. There are 921 aluminum cases placed in the walls’ cavity and with a total capacity of 460.5 kg of RT 25. The overall thermal capacity of the RT 25 placed in the walls’ cavity is 78.2 MJ. It is derived that the installation of a TESS in the walls’ cavity is capable to save energy consumption in the overall apartment energy use. Moreover the building’s energy efficiency increases significantly. The cost of the aluminum cases and placement of the cases in the walls’ cavity were not considered; therefore the cost of actual placement of PCM cases into the walls’ cavity will be greater.

8. Conclusions In this paper were presented the energy storage systems technologies and their implementation in RES. ESS can contribute in saving energy and preventing environmental issues relating to pollution and in clean energy production; where they can be used to transform RESHS into constant power suppliers to the demand grip. ESSs are categorized according the form of energy the store. The ESSs that were mention on this paper; except the capacitor; the FC; the TCESS and the CESS; are compatible with RES systems. Also presented in this paper was an implementation of thermal energy storage in the residential sector. A LHSS was placed in the walls’ cavity for storing the thermal energy losses of the apartment. After the calculation of the apartment’s thermal losses; a PCM was selected as storage medium. The thermal energy capacity of the PCM was found enough to carry out the storage of the apartment’s energy losses.

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