Indian Journal of Science and Technology, *Vol 9(30), DOI: 10.17485/ijst/2016/v9i30/99171, August 2016*
ISSN (Print) : 0974-6846
ISSN (Online) : 0974-5645

Creating Sustainable Environment using Smart Materials in Smart Structures

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Abstract

Objectives: The paper presents significant application of smart materials and their implementation in modern structures. The application of shape memory alloys, piezoelectric and magnetostrictive materials are provided in this paper for the readers. It also defines the architectural perspective in order to assess how architecture can develop with the advancement of smart materials. **Methods:** The scientific utilization of smart structural mechanics in the design, construction and preservation of infrastructures needs attention in civil engineering aspect. Smart meters are important components of next generation structures because they enable remote metering of energy consumption. The influence of TiO_2 coated plastering mortar, in its fresh state has good thermal performance in building wall model and makes the building thermally efficient. Additionally it includes the sustainable use and potential contribution of Zero Energy Building (ZEB) principle towards achieving smart cities. **Findings:** It is found that these technological strides can be used for better reliability and overall safety of any structure. Thus the structural integrity, firmness and long term benefits are taken care of. Finally we came up with the conclusion that the effectiveness of using smart materials in smart structures can become an agent in building "towards a new architecture". **Applications:** These materials are useful in creating a sustainable environment which are eco-friendly and leads to less energy consumption which is a boon to our society.

Keywords: Magnetostrictive Materials, Piezoelectric Materials, Shape Memory Alloys, Smart Meters, ZEB

1. Introduction

The different materials and methods that have been used has a significant impact on environment as well as on economy. Hence, the proficiency to make numerous environment friendly, economical choices without affecting materials efficiency, structural integrity, longevity, cost and industrial probity is of utmost importance[1]. New advance technologies and high performing materials are being developed to fulfill these needs, offering more innovative solutions for long term problems. They all provide benefits, whether it is structural firmness, environment, or for maintenance and repairing purpose[2]. There are two types of smart as smart materials and smart structures. The study and application of smart material in smart structures were developed by several authors. Smart materials like shape memory alloy, magnetostrictive materials, piezoelectric materials, Titanium Dioxide coated nano materials, architectural applications of these smart materials in the smart structures are given in details.

2. Smart Materials

Smart materials are those materials that can respond to any change in electricity, magnetic waves or heat[3]. They are able to receive and respond to any kind of stimuli from the environment as well as from their inner, and adapt the changes by integrating the functionality in their structures. Commonly, smart structures assimilate smart materials. These are not only smart in composition but also smart in adjusting with the structural changes. Smart materials are known to be ingenious instantly and innately identifying changes in the environmental conditions and giving response to those alterations with some kind of actuation or action[3]. Moreover, they show some proper actions or actuations introduced in response to identified

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environmental changes and conserve the states of material under consideration[4]. The stimulus and response can be of various types such as electrical, chemical, radiant, thermal, magnetic etc.

Smart materials are classified into the following categories.

2.1 Piezoelectric

These when directed to an electric charge or a fluctuation in voltage, piezoelectric material will go through some mechanical change and vice versa. These phenomenon are called the direct and converse effects.

2.2 Electrostrictive

They are of the same characteristics as that of piezoelectric material. This characteristic will always produce displacements in the same path. The mechanical change is proportional to the square of the electric field.

2.3 Magnetostrictive

When provided with a magnetic field, and vice versa (direct and converse effects), this material undergoes an induced mechanical strain. Eventually, it can be used as sensors and/or actuators. (Ex: Terfenol-D).

2.4 Shape Memory Alloys

When provided with a thermal field, this will undergo phase changes which helps in shape changes. It regains its 'martensitic' condition with low temperature, and gains back its initial shape in its 'austenite' condition when heated at high temperature. (Ex: Nitinol TiNi).

2.5 Optical Fibers

Fibers that use polarization, phase, intensity or frequency to determine strain, temperature electrical/magnetic fields, pressure and other measurable parameters. They are known to be excellent sensors[5].

2.6 Advantages of Smart Materials

The advantages of using smart materials are[1]

- Cost Effective.
- High strength, toughness.
- Increased durability.
- Have high resistance to chemical corrosion, abrasion.
- Tough against natural disasters.
- Manufacturing and installation procedures are easy.

3. Types of Smart Materials

3.1 Shape Memory Alloys

Shape Memory Alloy (SMAs) are types of alloys which recovers their normal shape and that when deform comes back to its original state. The material is of less weight, solid state option to habitual actuators such as hydraulic, pneumatic, motor based systems[5]. The applications are briefly discussed below:

- Couplings.
- Actuators.
- Smart materials.

Couplings are known for its effective use of SMAs. Applications as actuators in various fields like in electrical components, automobile, robotics etc are performed. Thermal conductivity of SMA is better, leading to excellent response on application of heat. SMA which are used as an actuator mentioned above act both as actuators and sensors. Thus, SMAs are called smart or intelligent materials[6].

These shape memory alloys which are commonly available are Cu-Al-Ni and Ni-Ti alloys. Besides the SMAs can be made by alloying zinc, copper, gold, iron etc. SMAs exists in various forms having three different crystal structures such as twinned martensite, detwinned martensite and austenite. These are characterized by recovery of usually large strains. In response to temperature the phase transformation between the martensite and austenite phases can be induced to mechanical stress. They are typically made by casting, induction melting.

3.1.1 High Temperature Shape Memory Alloy

The Zr-based quasibinary intermetallics are considered as more advanced, as they have high temperature upto 1100 K, related to a seemly higher temperature shape memory phenomenon. To carry out an evaluation of high temperature shape memory alloy behavior with their associated characteristics as in Ni–Ti–Zr, Ni–Ti–Hf and Zr–Cu-base quasibinary intermetallics, as these are the most promising advantage among all of the less expensive HTSMA[7].

3.2 Magnetostrictive Material

Magnetostriction is a characteristic property of ferromagnetic materials which possess them to alter their shape, dimensions in the process of magnetization as shown in Figure 1.

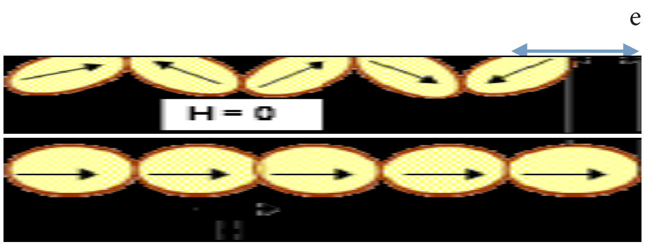


Figure 1. Magnetostriction (e) in materials under the influence of applied magnetic field H due to domain migration and reorientation.

The magnetostrictive materials can change magnetic energy to kinetic energy and vice versa, can be used to build actuators and sensors. If the magnetic field is given in the direction of an applied stress, the resultant magnetostriction will be larger than that without pre-stress. Iron, nickel, and cobalt were the first three magnetostrictive materials. Table 1 illustrates different types of magnetostrictive materials. Legvold and Clark discovered giant magnetostriction in the rare earth materials Dysprosium and Terbium. Later alloys called Terfenol-D comprises of Terbium, Dysprosium and Fe which shows the best option between a greater magnetostriction and a lower magnetic field, at normal room temperature. A definite magnetostriction of 1000-2000 ppm is achieved with fields of 50 kA/m-200 kA/m. Terfenol-D is most available material for use in many fields. Lead Zicronate Titanate (PZT) is a piezoceramic material that has low cost, light weight, high energy density, and easy to implement[8]. The magnetostrictive material, its working mode, its dependence on Magnetic Field in Figure 2. The configuration and use of actuators in magnetostrictive materials is given in Figure 3.

3.3 Piezoelectric Materials

The Piezoelectricity is a characteristics shown by materials which becomes charged if directed to electricity and also directed to mechanical stress. Crystals like quartz, Rochelle salt, and tourmaline shows piezoelectric effect[9]. This effect is due to a disallignment in the primary cell, association amongst mechanical deformation and the electric dipole differentiation. Piezoelectric charge coefficient is a relation between charge and provided force that produced the charge whose unit is Coulomb/Newton.

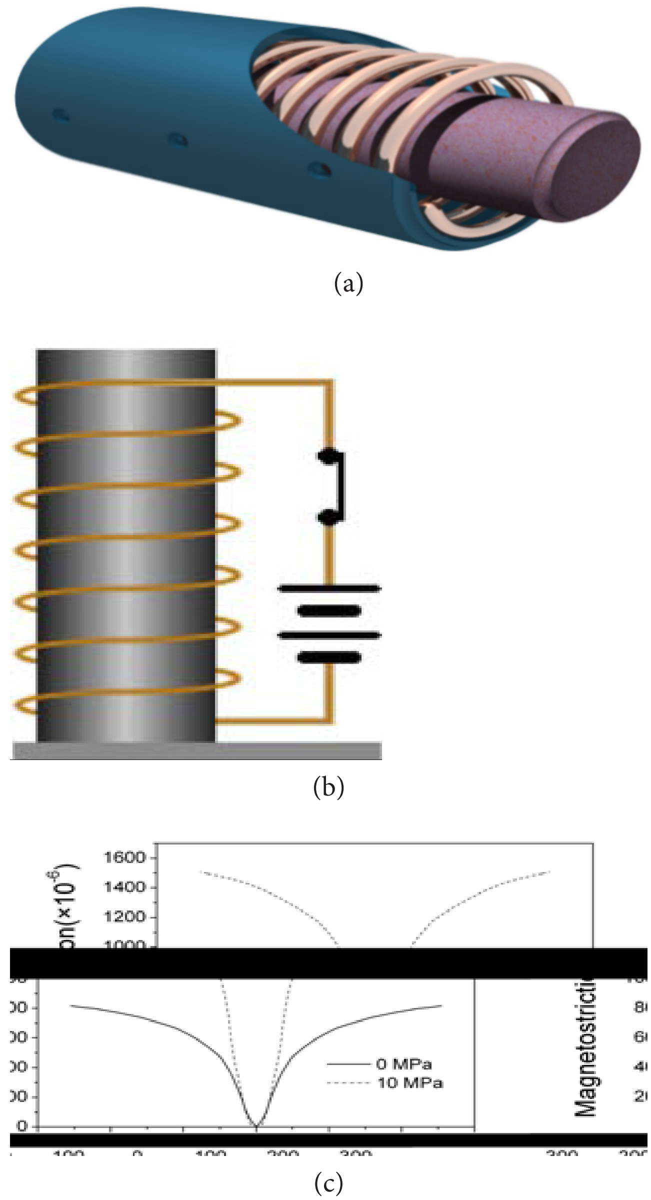


Figure 2. (a) Photo of magnetostrictive material. (b) Working mode. (c) Dependence of magnetostrictive on magnetic field.

$$d = \frac{\text{Generated Charge Density}}{\text{Applied Stress}}$$

The coupling coefficient is a relation between mechanical energy collected after providing an electrical input and its reverse is also possible[10]. Hence, the square of coupling coefficient is given by the formula,

$$K^2 = \frac{\text{Electrical Energy Saved}}{\text{Mechanical Energy Provided}}$$

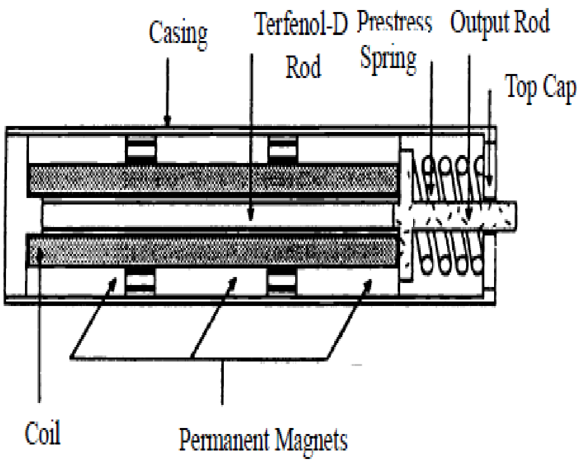
Conversely,

$$K^2 = \frac{\text{Mechanical Energy Saved}}{\text{Electrical Energy Provided}}$$

Where, d and k are given by matrix quantities dij and kij,

i = Applied electric field direction.

j = Stress or Strain direction.



(a)

(b)

Figure 3. Typical. (a) Configuration. (b) Photo of actuators using magnetostrictive materials.

They are prepared by fine powders of component metal oxides (PZT or Barium Titanate family) e.g., for PZT you need PbO, ZrO_2 and TiO_2 powders

- Mix them in fixed proportions.
- Use an organic binder.
- Form into specific shapes.
- Heat for a specific time and specified temperature 650-800°C.
- Cool – apply electrode (sputtering).
- Polarize the sensor/actuator using a DC electric field.
- Lead Zicronate Titanate (PZT): It comprises of Lead Zicronate and Lead Titanate. PZT ceramics posses some properties like higher piezoelectric activity, less temperature, time steadiness and classified as hard or soft. PZT is shown in Figure 4[8].
- Lead Titanate: Lead titanate constitute of some high anisotropic properties. They are mostly utilized to remove obstruction from radial modes. Lead Titanate without any impurities is having the maximum Curie temperature. Figure 5 shows the Lead titanate structure.
- Pb Mg Niobate - Lead Titanate (PMN-PT): They exhibits low hysteresis and higher strain value. It is the type of electrostrictive material which is having square dependence law of strain and the given electric field. Figure 6 shows the working model of PMN PT[11].

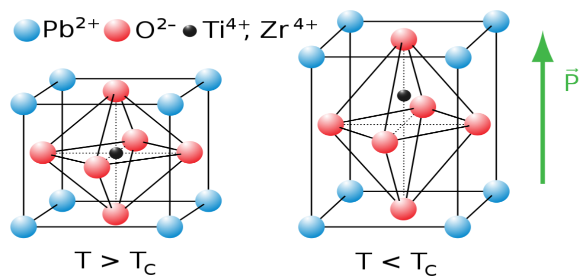


Figure 4. PZT.

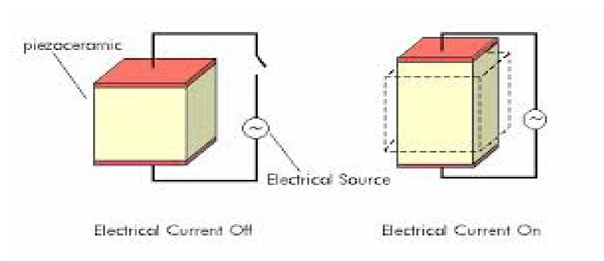


Figure 5. Lead titanate.

3.3.1 Applications of Piezoelectric Materials in Smart Structures

- Active Vibration Control: Distinct piezoelectric patches help to regulate the vibration associated with thin plates in smart structures.
- Active Sound Control: It was used to eradicate or eliminate the different types of sounds produced. The significance of active sound control in the

work place is of utmost importance as because hearing loss can occur from long term exposure to workplace sound.

- Active Control for Shape: Used as reflectors and antennas that maintains accurate dimension for best possible results. Its of primary importance in 3D structures comprising light weight material and is allowed to thermal distortion.
- Active Health Maintenance: Structural panel consisting of a series of actuators and sensors actively regulate the structural integrity and identify defects earlier, hence providing information on structural defects and its life span. Figure 7 shows piezoelectric fan blades locating the actuator and sensors12.

3.4 TiO2 Coated Surfaces as Resourceful Energy Saving Technology

TiO2 based white pigmented powders are used in industries due to low cost, low toxicity, high chemical stability and availability. These materials are used to produce surface with photo-catalytic, antibacterial, self-cleaning nature based on its photo-induced hydrophilicity/hydrophobicity and decomposed photo reactions. It helps to increase the light absorption capacity due to the surface/volume relation of nano grains. This is very advantageous because even a small amount of water would be sufficient to form a water thin film on the buildings as well as decreases the supply of electricity by traditional air conditioning13.

3.4.1 Preparation of Mortar

The aqueous solution of TiO2 are sprayed on to the mortar surface when the mortar is fresh. This solution is prepared by 1% of TiO2 by weight and 1% by acrylic binder on the solution. The spraying process is important because the sunlight is absorbed by the TiO2 particles, it helps to avoid the waste of semiconductor material cost that arises from the volume addition of TiO2 nano particles14.

4. Techniques used in Smart Structures

4.1 Smart Windows

Window technologies made up of suspended particle device act as “light valve” in monitoring the amount of light which passes through the windows as shown in Figure 8. These acts as energy efficient cost efficient and affordable. The convergence of the architectural trend towards more use of glass (including growing interest in day lighting) and increasing demand for reducing energy use creates a unique opportunity for smart windows[15].

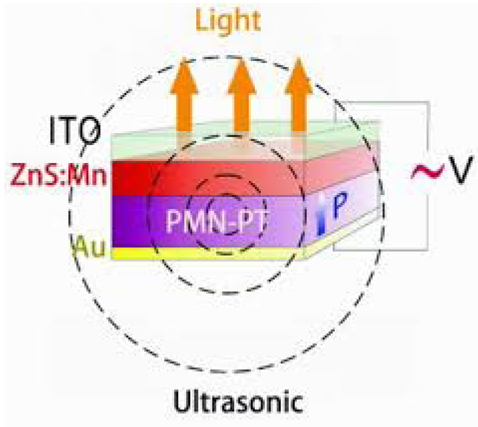


Figure 6. PMN PT.

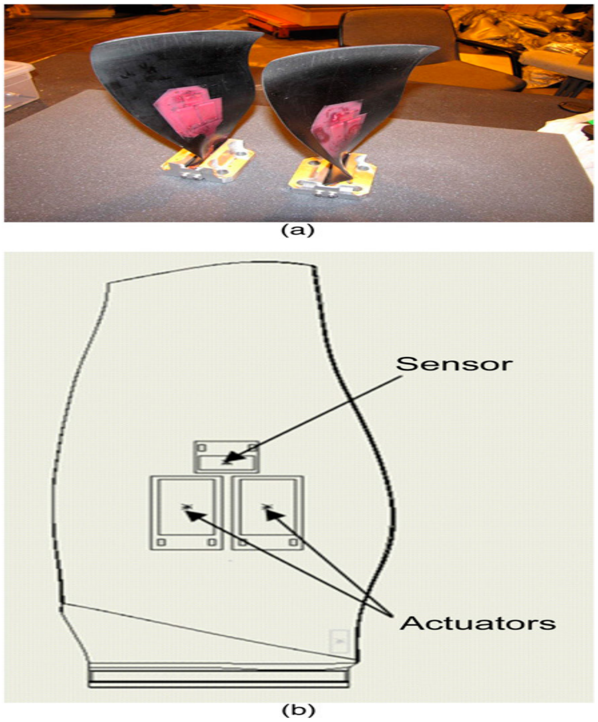


Figure 7. Piezoelectric fan blade test. (a) Photo. (b) Blade locating actuators and sensors.

4.2 Smart Shade

These are made up of zinc and steel to monitor the amount of sunlight entering the structures using shape memory alloys wires and regulate the amount of CO_2 in the room as shown in Figure 9. Air that flows inside the room unless there is an equilibrium with the air outside. 'Smart Window Shade' which is the self-adjusting window shade. It automatically opens up and closes by itself. The Computer terminal acts as a remote to distribute instructions to the window shades. These hand adjustments are stored into the microcontroller's system along with the room's current light and temperature. The window shade will automatically readjust itself when lighting and temperature conditions are found in the room[16].

Figure 8. Smart window.

Figure 9. Smart shade.

4.3 Roofing.

Photo voltaic modules are integrated into roofing materials and are mounted on the roof top racks. PV roofing produces free electricity from sunlight that can power the electricity needs of the house as shown in Figure 10. Its initial installation cost is high but maintenance cost is low. The energy required to produce Photovoltaic (PV) panel and maintenance of structural components is noted for evaluation of energy remuneration time and CO_2 production of the 1.2 PV rooftop systems. Photovoltaic energy (PV) have more potential than other power supply without any limitation on CO_2 release, specifically for small circulated heat and electrical energy generation process[17].

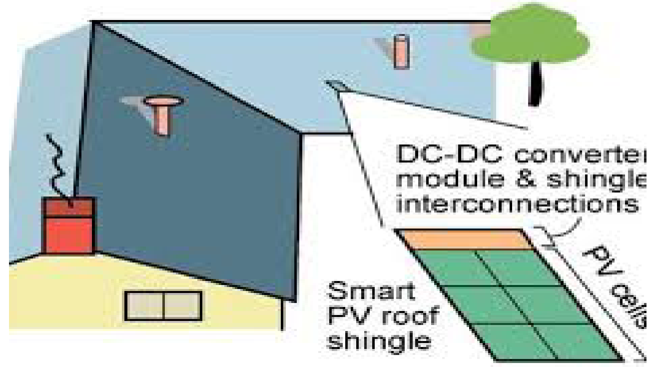


Figure 10. Smart roof using pv cells.

4.4 Ceilings

These include antibacterial coating that destabilizer the cellular membrane of certain micro-organisms preventing them from multiplying and surviving. The coating helps to control the odor and stain causing bacteria on ceiling tiles. It requires change in the whole surface mostly with water resistant polymeric surface coatings. These components are created as non-smelling, which means protein adsorption and succeeding microbial grip are decreased[18]. Assimilation of antibacterial promoter in a huge mass or as surface coating are taken as a workable substitute for systemic use in antibiotics. Moreover, appearance of variety of drug resistant bacterial strain restricts the application of antibiotics in a more convenient way[19].

4.5 Smart Concrete

Carbon fibers which are added to the concrete mixture helps to detect stress and small deformations in concrete[20]. Carbon-Fiber Reinforced Plastic (CFRP) structures utilizes an electrical network of conductive carbon fibers as a distributed sensor network by properly locating electrodes on structure. Figure 11 shows a bioconcrete sample[21].

Figure 11. Bio concrete as a smart concrete.

4.6 Smart Bricks

Bricks having sensors, signal processors and wireless communication links as shown in Figure 12 which warns about hidden stresses or damage through natural disasters. This help to regulate temperature vibration and moment[22].

Figure 12. Smart brick.

5. Architectural View of Smart Structures

The expansion of smart structural mechanism and its execution in the design, retainment, construction and repairing of infrastructures are required for the performance improvement, functioning effectiveness, safety, and dependability of structural systems, specifically in regions subjected to natural disastrous events. Figure 13 shows the core components of smart structure[23].

5.1 Zero Energy Building (ZEB)

Zero Energy Buildings (ZEBs) are mentioned as buildings which are having zero carbon emissions on yearly basis. In practice this is achieved by decreasing the energy requirement of the infrastructure by exploiting RES by appropriate technologies to fulfill energy requirements. Thus, definitions vary due to discrepancies in the absolute level of energy consumption in a low energy building, and also to differences of the minimum requirements as stated in the national building regulations .

The most dominant terms for defining a ZEB are:

- Use of zero site energy.
- Use of zero source energy.
- Total zero energy discharges.
- Total cost.
- Off-grid.
- Energy plus[24].

ZEB is a type of building that consumes a total zero energy from non-renewable sources. The ZEB buildings are very much energy effective and can rely on renewable energy generated on site.

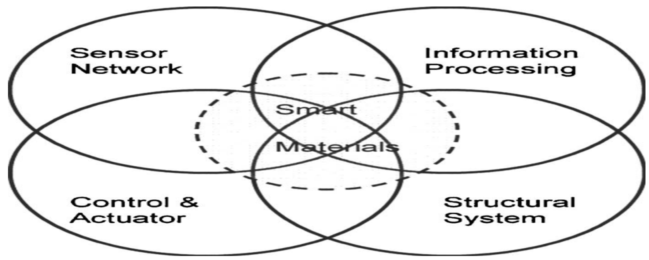


Figure 13. Core components for smart structural system.

5.1.1 ZEB as Integral Part of Smart Cities

The methodology of the analysis intends to demonstrate the potential of ZEBs in contributing to the development of smart cities. Primarily, the provisions of a ZEB that will be considered as an integral part of a future smart city will be identified and presented in Figure 14. Following are the identification of the elements of ZEBs that can significantly contribute to the development of smart energy cities, this paper will attempt to quantify this contribution. The concepts formulating the analysis include:

- Environmental design and building practices.
- Renewable Energy Sources (RES)
- Labeling of technical building systems.
- Intelligent Energy Management[25].

5.2 Smart Meter as a New Technology

Smart meters are an important component of next-generation smart grids because they enable remote metering of energy consumption (including electricity, water, and gas) and provide more information than a conventional energy meters[26]. An significant characteristics of smart meters is their use of fast, consistent and safe and sound data communication networks to effectively and intelligently supervise complex power systems Figure 15 schematically represents how the physical and functional aspects of smart meters used for energy measurement. The system architecture comprises three parts: The interior residential network referring to metering and sub-metering infrastructure, the communication network, and the data collection and management infrastructure[27].

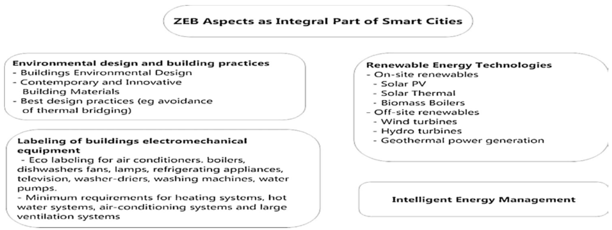


Figure 14. ZEB aspects as integral parts of smart cities.

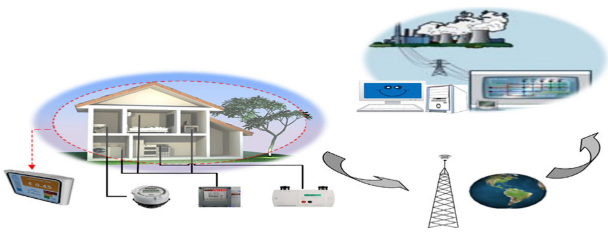


Figure 15. Smart meter system architecture.

5.2.1 Smart Meter System Benefits

The advantages of smart metering installation are abundant for many different customers of the systems. The table given below shows some of the important profit for convenience of customers[28].

Table 1. Different magnetostrictive materials

Material Magnetostriction	Curie (ppm)	Temp (K)
Fe	14	633
Co	50	350
Permalloy	27	713
$DyFe_2$	650	635
$TbFe_2$	2630	703
Tb.6Dy.7Fe1.9	2400	653

6. Conclusions

The smart structures are constructed with using smart materials and it has got many advantages. The use of smart material namely shape memory alloy is useful because it bents at low temperature and on heating regain its initial shape. The use of magnetostrictive material is that they can change magnetic energy into kinetic energy and vice versa which are used as actuators and sensors for buildings. The piezoelectricity is a state of smart materials which becomes electrically charged when directed to mechanical stresses and vice versa. The use of Titanium Dioxide as a smart material has also gained advantage because it has high fundamental characteristics such as low toxicity, high chemical firmness; it also helps to improve light absorption by means of surface/volume ratio of nano grains. The properties of smart window, smart shade, smart roofing, smart ceiling, smart concrete and smart bricks also have good characteristics for building smart structures.

The use of zero energy building is in great progress across many countries as it helps in less consumption of electricity. It has zero carbon emission in an annual basis which is environment friendly. Smart meters are also important because they enable remote metering of energy consumption and gives more data about conventional energy meters.

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