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## Numerical Examination of Metamaterial Concentrator Design for High Efficient Thermal Energy Harvester

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## Numerical Examination of Metamaterial Concentrator Design for High Efficient Thermal Energy Harvester

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**Abstract.** Nowadays, research on energy harvesting is highly interest to harvest more waste thermal energy which produced by any kind of thermal engine in our daily life. Thermal metamaterials, designed by transformation thermodynamics are artificial structure that can actively control heat flux at a continuum scale. However, right now the problem of using metamaterial on thermal harvesting is to know what is the best shape design, configuration, and best material to obtain highly efficient on thermal energy harvesting because of the number of research on this field is limited. Flower-shaped metamaterial thermal concentrator has developed and it showed that the design can performed well on directing heat flux to specific location. However, the Flower-shaped metamaterial design that has been conducted before not optimized yet. In the current paper, the numerical simulation and analysis for several metamaterial and shape construction variations were performed using Ansys Workbench™ to characterize the best configuration to optimizing flower-shaped thermal concentrator. A number of interesting numerical computation presented on this research manuscript including total heat flux, temperature distribution, and thermal concentrator efficiency on the surface of the constructed concentrator. The aim of this paper is to provide more reference on metamaterial design for thermal harvesting.

Keywords: Energy Harvesting, Thermal Concentrator, and Metamaterial

### 1. Introduction

Energy is one of the most important need for human daily activity and also to drive and powering mechanical and electrical devices on industrial activity. However, according to US Department of Energy it has estimated that as much as 20 to 50% of the industrial activity total energy consumption discharged as waste heat from various device. While some waste heat losses from industrial processes are inevitable, facilities can reduce these losses by improving equipment efficiency or installing waste heat recovery technologies. To harvesting thermal energy from waste heat, it is needed a medium that can be used as a collector of heat from a flow of heat flux. A collector theoretically can be more efficient to harvesting

thermal energy whenever the heat flux from arbitrary direction can be concentrated to some core or a specific location. Harvesting thermal energy through heat flux manipulation and focusing has been proposed by researchers as a practical extension of work on thermal metamaterials, and has practical applications for autonomously powered sensors or self-actuated devices (Dede et al, 2016).

One of the research on thermal concentrator has been proposed. The type of thermal concentrator proposed by Liu et al (2017) is configured as called Flower-shaped thermal energy harvester made by metamaterials. The design has been examined numerically and experimentally and provide excellent concentration efficiency with remarkable energy density increase and the temperature gradient intensifies in the target core, while temperature profile keeps undisturbed. However, Liu et al (2017) just examined one type of flower-shaped thermal concentrator configuration design, with one type of metamaterial configuration.

Therefore, on this research numerical study is conducted with several design flower-shaped like thermal concentrator design, with each design simulated with 4 type of metamaterial configuration. The objective of this research is to find the optimum result of flower-shaped-like thermal concentrator configuration that can provide more efficiency on flower-shaped metamaterial thermal concentrator.

## 2. Method

In this research, the model of thermal concentrator is design with took basis on the thermal concentrator that was developed by Liu et al (2017), with 3 type of improved design configuration and simulated with 4 type of material configuration. The numerical simulation in this research use transient thermal analysis features from Ansys Workbench™ software. For the measurement of the concentration effect, the temperature of plane at hot section and cool section is set as  $T_1=150^\circ\text{C}$  and  $T_2=70^\circ\text{C}$ . In this research, the simulation is set with neglecting the effect of convection heat transfer phenomenon occur. The result of numerical simulation on this research presented on graph of Temperature vs location, with plotted location on each design. The graph that contain all type of metamaterial configuration temperature vs location graphic then analyzed to find the optimum configuration of flower-shaped like thermal concentrator design by measuring the thermal efficiency of the concentrator and then making comparison with the thermal concentrator that has been designed by Liu et al (2017).

## 3. The Concept of Thermal Energy Harvesting Concentrator

The basic concept of the design in this research is using flower-shaped thermal concentrator that has been developed by Liu et al (2017). The concept of directing heat flux has been explained well by Bandaru et al (2015) with the equation of heat flux angle below.

$$\theta = \text{Tan}^{-1} \left[ \frac{(-1 + c) \sin(\theta) \cos(\theta)}{\cos^2(\theta) + c \sin^2(\theta)} \right], \text{ with } c = \frac{\left[1 + \left(\frac{k_1}{k_2}\right)\right]^2}{4 \cdot \frac{k_1}{k_2}}$$

The equation then become the basis of flower-shaped configuration by using some configuration of metamaterial that has been arranged to get heat flux angle of direction that can direct to the center of the design to made a thermal concentrator. This design has been performed well by Liu et al (2017) on their research for thermal concentrator.

With the basis of design that performed by Liu et al (2017), then on this research the aim is to improve and optimize flower-shaped metamaterial thermal concentrator design. The idea to improve the design is first, using triangular fin-shaped design (three-dimension perspective) on the petal section of flower-shaped metamaterial thermal concentrator because the lower rate of triangular fin-shaped on dissipated heat to its environment compare than rectangular fin-shaped that Liu et al (2017) used. The reason of this idea because on thermal concentrator application, the aim of petals section is just to transfer and

concentrating heat to the specific location, or in this research is the core section of flower-shaped metamaterial, not to dissipate it to the environment like application of fin-shaped on heat sink and the other cooler devices. The idea of fin-shaped design on heat transfer application has been widely broad for many application, especially for triangular fin-shaped because the lower of total volume needed of triangular fin-shaped design on heat transfer application, but have lower heat transfer application compared with rectangular fin-shaped. Several authors has been investigated the efficiency of triangular fin-shaped and compare it to the rectangular fin-shaped (Mirapalli and Kishore (2015), Pirompugd and Wongwishes (2013), etc), it is can be concluded that triangular fin-shaped design have lower Biot number on transferring heat compare with rectangular fin-shaped design because triangular fin-shaped have less surface area. Otherwise, in this research the concept of the material that used in this research is using combination of three materials with different thermal conductivity to directing heat flux to specific location, this concept then become thermal metamaterial. The concept of metamaterial in thermal directing application has been explained and applied by several author (Yang et al (2014), Chen et al (2015), Han et al (2014), Peralta & Fachinotti (2017)). Based on that, in this research the material that used is the material with that have higher thermal conductivity as a heat flux director, and lowest thermal conductivity as a substrate between director to keep the heat flux flow in the director material, and material with mid thermal conductivity like stainless steel as a background and core section of flower-shaped metamaterial to be an intake section and the collector of the heat flux. In the concern of daily application and feasible of manufacturing or fabrication, in this research the configuration of metamaterial just varied in the substrate section with four type lower conductivity material which easy to get, and keep the background, core, and petals section in one type of material which also easy to get. The list of all material thermal properties in this research can be seen in the Table 1.

**Table 1.** List of all material thermal properties in this research

Materials	Density ( $\text{kg m}^{-3}$ )	Specific Heat ( $\text{J kg}^{-1} \text{C}^{-1}$ )	Thermal Conductivity ( $\text{W m}^{-1} \text{C}^{-1}$ )
Copper	8933	385	400
Stainless Stell	7750	480	15.1
PDMS (Polydimethylsiloxane)	1460	970	0.15
Polyimide	1400	1150	0.25
Thermal Epoxy	1900	1150	0.249

The base design that has been designed by Liu et al (2017) and all the design with several material configuration of metamaterial thermal concentrator that has been designed in this research is shown in the Figure 1. The thickness of all the metamaterials design that designed in this research is 0.5 mm, similar with the thickness of metamaterial that designed by Liu et al (2017).

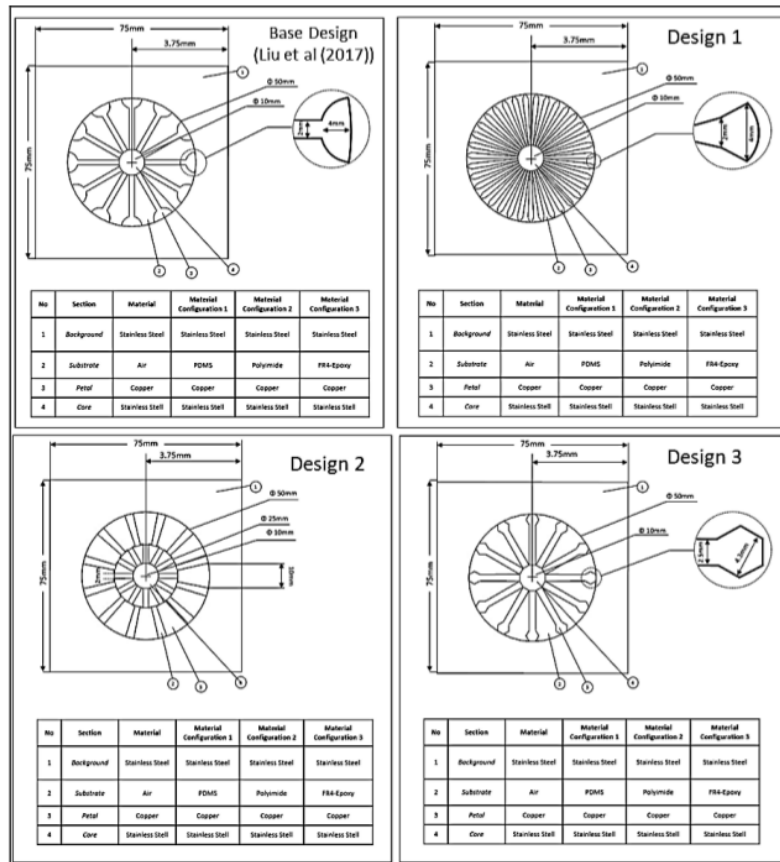
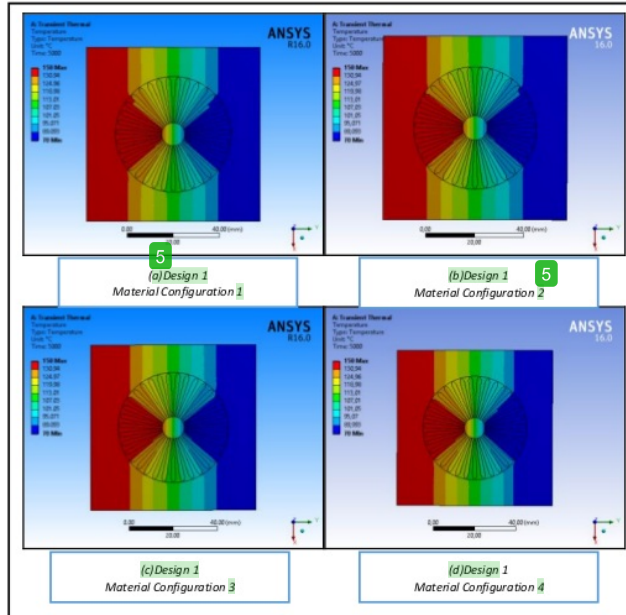


Figure 1. Design of thermal concentrator metamaterial in this research

#### 4. Result

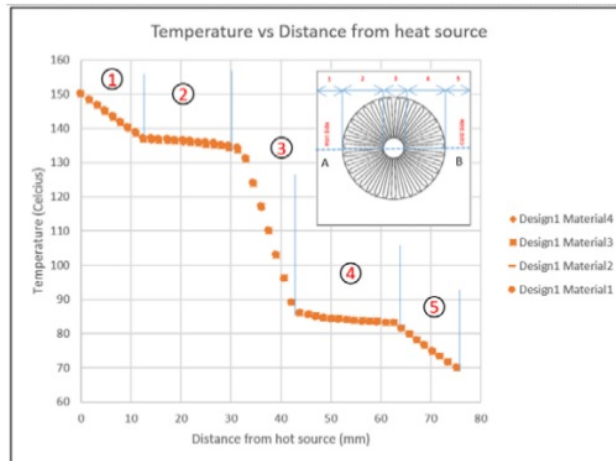
##### 4.1 . Effect of Material configuration

Based on the result of numerical simulation, the effect of the material configuration that used in this research is less to the thermal distribution and concentration in the metamaterial. This result can be seen in the Figure 2 that shows the temperature distribution of metamaterial concentrator with using Design 1 as an example of the result.



**Figure 2.** The Temperature distribution of metamaterial concentrator for every material configuration with using design 1 as an example of the result

The same result is occurs for other design that used in this research. More detail temperature distribution comparison for all material type that used in this research across the Design 1 can be seen in the Figure 3.



**Figure 3.** Temperature profile along Design 1 with different material configuration

The reason of this phenomenon is because the differential of material configuration in this research is just on variation in the substrate section design. Furthermore, the difference of thermal conductivity for each material that fill the substrate section is small. But from the analysis of concentrator efficiency that showed in Table 2, the lower of substrate section thermal conductivity, higher concentrator efficiency. As we can see the design that using air as the substrate ( $k = 0.026 \text{ W m}^{-1}\text{C}^{-1}$ ) is more efficient than PDMS ( $k = 0.15 \text{ W m}^{-1}\text{C}^{-1}$ ) and so on.

#### 4.2. Effect of Improved Design

The idea of improved design in this paper is based on the concept of heat transfer phenomenon in the triangle fin-shaped for Design 1 and Design 2. The concept of heat transfer with triangle fin-shaped has been explained in the Design Concept section. The Design 1 is designed with small triangle shape-like on the outer circle of concentrator and then with more narrow triangle fin shaped-like petals, and as the result, the Design 1 have small petals with more petals than the other design, with total 35 petals. The Design 2 is designed with more broad triangle fin shaped-like, and the shape is build from the outer circle with length 25 mm, and then continued with rectangle fin-shaped like petals to the core outer diameter. The Design 3 is The Design 3 is one of the design that designed with arbitrary design on the metamaterial concentrator petal section. This design was purposed to be design that to be reference for the design that designed with arbitrary shape compared with conceived design. The result of transient thermal and total heat flux concentrated numerical simulation for each design with using example of material configuration 2 (Using PDMS as substrate, with  $k = 0.15 \text{ W m}^{-1}\text{C}^{-1}$ ) can be seen in the Figure 4 and Figure 5.

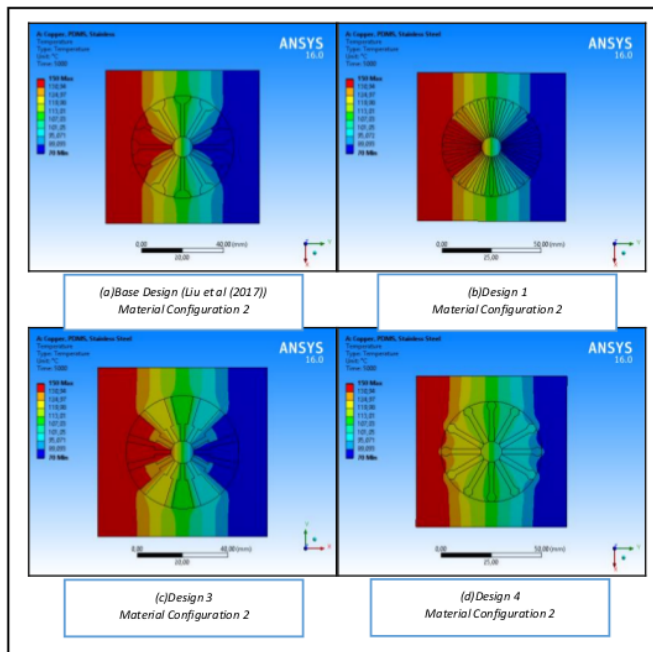
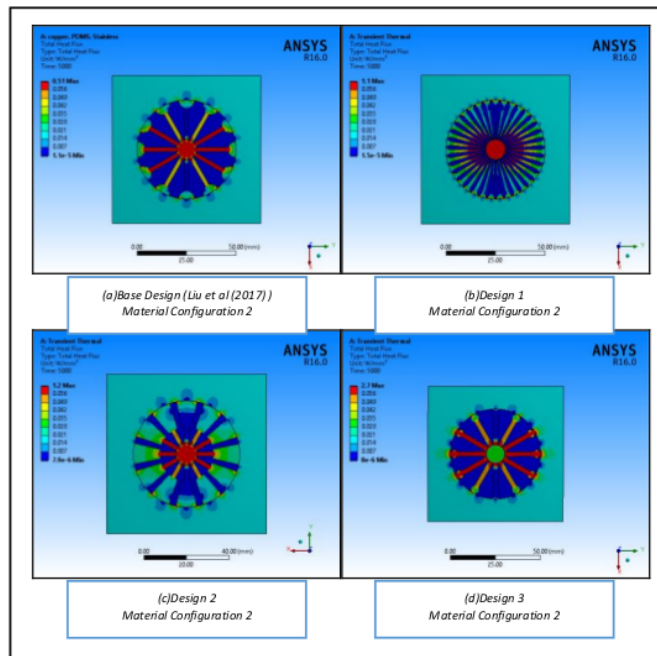


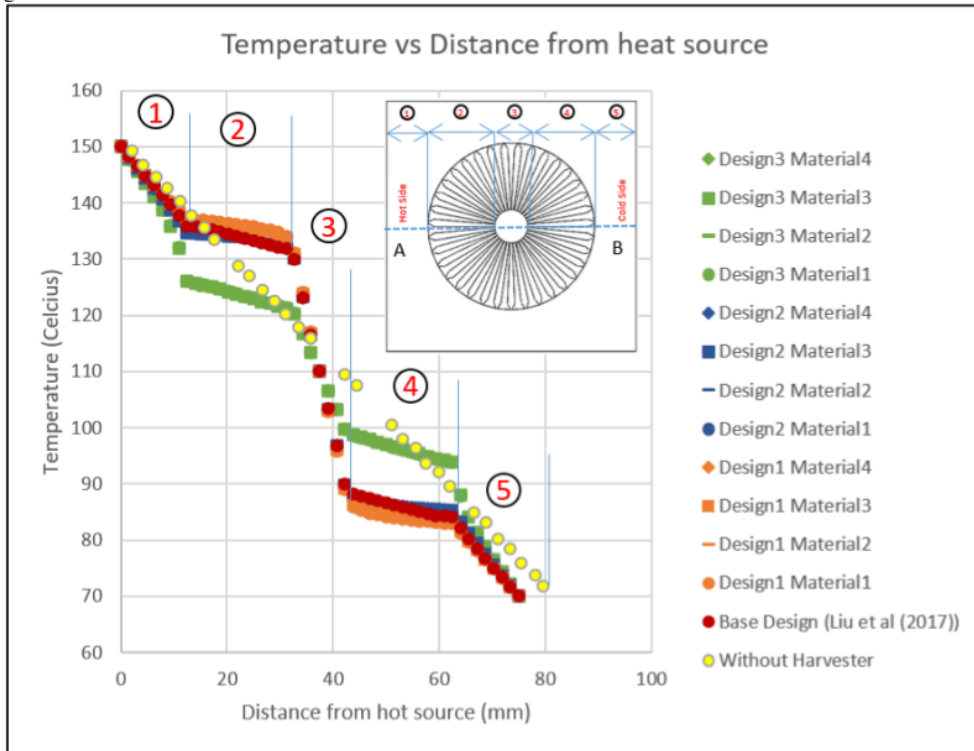
Figure 4. Temperature distribution on each design 2D plane, with using Material Configuration 2 as comparison



**Figure 5.** Total heat flux distribution on each design 2D plane, with using Material Configuration 2 as comparison

From Figure 4 and Figure 5, we can see the result of simulation showing that the Design 1 on figure (b) have more sophisticated result on the thermal concentration function compared with other design. The design can harvest heat flux from wider area of heat source and then concentrated it well on the core section of concentrator, indicated by highest temperature indicator and highest total heat flux collected (red scale) that can be narrow to the core with more area on the core surface with highest total heat flux the design can get in core is  $1.1 \text{ W/mm}^2$ . The design from Liu et al (2017) that showing by base design on figure (a) of Figure 4 and Figure 5, showed that higher temperature and higher total heat flux collected (red scale) cannot concentrated well on core section of metamaterial design, with higher temperature range just directed by one petals, and have a lot of heat loss to the director material surround, so the maximum of heat flux the design can get just  $0.51 \text{ W/mm}^2$ . The idea of making triangular fin-shaped like more broad with less amount of petals section on the Design 2 also have less efficient thermal concentration behavior, it is can be seen on the figure (c) of Figure 4 and Figure 5, but even better than Base Design by Liu et al (2017). The concentration on higher temperature in initial phase can be directing by broad triangular fin-shaped-like, but then the temperature just drop to lower temperature range scale at the point where the rectangular fin-shaped applied, and so the total heat flux (red scale) cannot distributed well on the core section like Design 1, even it is have slightly more higher value of total heat flux compared with Design 1, but the difference just  $0.1 \text{ W/mm}^2$ . The Design 3 is the worst result among all, it is can be seen on figure (d) of Figure 4 and Figure 5, it has been predicted because the design was designed with arbitrary shape design. The temperature profile along all the metamaterial on this research is showed on

the Figure 6 below. The temperature profile is taken from the point A to B as it shown on the Figure 6 legend.



**Figure 6.** Temperature profile along all the metamaterial design on this research

The zone of temperature profile is divided into five section, that is the number 1 is background section zone, from the edge of hot side until boundary of concentrator outer circle, number 2 is petals section which is from the boundary of concentrator outer circle into boundary of concentrator inner circle, number 3 is along diameter of core, number 4 is from the right side of inner core boundary into the right side of outer circle boundary, and the number 5 is from outer circle boundary to edge of cold side material. From the chart on Figure 6 we can see that the metamaterial with Base Design, Design 1, and Design 2 can concentrated heat well on the edge of core section so the temperature remain high, compared with temperature profile of material with no thermal concentrator or harvester. The more specific value of thermal concentrator comparison in this research is can be seen on the Table 2, which is showed the efficiency of all metamaterial thermal concentrator that studied in this research.

**Table 2.** Concentrator efficiency of all the metamaterial design on this research

Design Compartment		Thermal Efficiency
Base Design (Liu et al (2017)	Material	88.14%
	Design 1	
	Material	
	Configuration 1	89.86%
	Material	
	Configuration 2	89.68%
	Material	
	Configuration 3	89.62%
	Material	
	Configuration 4	89.57%
Design 2	Material	
	Configuration 1	88.66%
	Material	
	Configuration 2	88.49%
	Material	
	Configuration 3	88.35%
	Material	
	Configuration 4	88.29%
Design 3	Material	
	Configuration 1	81.20%
	Material	
	Configuration 2	81.16%
	Material	
	Configuration 3	81.13%
	Material	
	Configuration 4	81.11%

From the table 2 we can see that the best design among all is the Design 1, with the most sophisticated result of concentrator efficiency is by Design 1 with Metamaterial Configuration 1, with efficiency is 89.86 %. But for practical application, may the Design 1 with Metamaterial Configuration 2 is more applicable which is using PDMS as substrate with efficiency 89.68 %, different with Metamaterial Configuration 1 which is using air as substrate. It is because air is an unstable matter, which the properties can be varied, depend by environment condition.

### 5. Conclusion

From the result on this research, it is can be concluded that metamaterial with flower-shaped like design can harvest thermal to the specific location, and the flower-shaped metamaterial that developed first by Liu et al (2017) can be optimized with using improved design like Design 1 with triangular fin-shaped like in petals section with less Biot number compared than rectangular fin-shaped of director material. Also, from the result of comparison between Design 1 and Design 2 we also can get that the more petals also can get higher thermal concentrator efficiency.

The incremental of thermal concentrator efficiency which achieved with Design 1 up to 1.72 % and the incremental of total heat flux can be harvested is 116% (two times as larger as), compared with the Base Design which designed by Liu et al (2017). Otherwise, in this research is also studying about several material configuration with just varying substrate section with four type material, the result is like in the table 2, the incremental of concentrator efficiency is very low, that is because the difference of thermal conductivity is also less. But from the table 2 we can conclude that lower the substrate thermal conductivity, the more efficiency of thermal concentrator we can get.

The limitation on this research is the design that conducted in this research have not been fabricated yet, so further study needed to fabricated the design, so it is can be see the design performance as physically.

In the future research it is can suggest that more study to exploring new design configuration or material configuration with recent material technology that can have much higher or even lower thermal conductivity to applied for thermal concentrator is very needed to gain more thermal concentrator efficiency than this research can gain. Otherwise, the design was studied in this research just take design in millimeter scale of size, it is maybe can be conducted research that perform analysis of metamaterial thermal concentrator which has smaller size until nano-sized metamaterials. Furthermore, further study and development of the current research activity is the best reference to contribute the manufacturing of metamaterial to support highly thermal energy harvesting efficiency such as applied on thermoelectric generator, and has practical applications for autonomously powered sensors or self-actuated devices compact power supply of low power consumption appliances and so on.

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