Combining light-emitting diode and gravity light to generate power continuously

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Abstract

Alternatives to kerosene lamp have been explored for people who do not have access to electricity in developing regions. GravityLight (GL) uses stored gravitational potential energy to power light-emitting diode (LED). Both LED and GL are reviewed for main characteristics and mechanisms. An improved GL system is proposed targeting continuous power generation, the design principles of which are established from the law of Conservation of Energy. The system might be made possible by energy storage and bringing in other forms of energy/work. The proposed solution is evaluated to be feasible.

Nomenclature

λ	Wavelength
c	Speed of light in a vacuum inertial frame
E	Energy
f	Frequency
h	Planck constant
h_0	Height
U_g	Gravitational potential energy
W	Work

CFL	Compact fluorescent lamp
FMEA	Failure mode and effects analysis
GL	GravityLight®
HSE	Health, safety, and environment
LED	Light-emitting diode
RSA	Regenerative shock absorber

1 Background

The demand for energy has ever been increasing since decades if not centuries ago, due to the continuous growth in world's population and the advance of technology, from drilling deeper into the earth as well as traveling further in the universe. The situation is more pronounced after some major incidents involving renewable energy, for example the Fukushima Daiichi nuclear disaster. There is no doubt more research on renewable energy needs to be conducted: fossil fuels are limited. In the meanwhile, making current energy consumption more efficient is attractive and indispensable. With a certain amount of electricity generated from fossil fuels (non-renewable energy), are there any possibilities to power more light bulbs? The answer is yes and those options must be implemented. Light-emitting diode (LED) is such an example that makes electricity consumption by light bulbs very efficient.

Another aspect of the challenges is people in some developing regions still do not have access to stable and reliable electricity supply. Kerosene lamp is being used for household lighting. Kerosene lamp introduces greater risks of fire-related injuries (Chamania et al., 2015), and is associated with harmful effects to human being's health due to indoor air pollution (Pokhrel et al., 2010). On top of that, this lighting method is not cheap – on average it accounts for one fifth of the household income (Brown, 2013). Are there any alternatives shown to be safer, healthier, and cheaper? GravityLight® (GL) is one solution that has been proposed.

Both LED and GL are to be discovered in the next section.

2 A Brief Introduction to LED and GL

2.1 LED

Light-emitting diode, or 'LED', is a p-n junction diode which emits light when it is forward biased. Since normal p-n junction diode does not emit lights under forward bias, it is worthy explaining what is special about LED.

When any diode is forward biased, electrons and holes will go through recombination. During the process, energy is dissipated in the form of photons. More specifically, it is free electrons that jump from conduction band (high energy level) to valence band (low energy level), and emits photons (Figure 1). The equation for photon energy, given by Planck–Einstein relation, is:

$$E = hf \tag{1}$$

where E is photon energy, h is Planck constant, and f is frequency.

Since $f = \frac{c}{\lambda}$, Equation 1 can be re-written as:

$$E = \frac{hc}{\lambda} \tag{2}$$

where c is the speed of light and λ is wavelength.

Thus wavelength is correlated with energy gap (between conduction band and valence band). In normal diode, this energy is in infra-red range which is invisible in most situations. LED, on the other hand, can emits light with distinct colors. On a more fundamental level, this is due to the difference in materials from which normal diode and LED are made.

One advantage of LED over traditional lighting options is its higher efficiency. LED works longer than incandescent light bulbs, if on same electricity and lumens benchmark. This is due to the fact that most of the electrons will transition into photons at p-n junction; only a small portion will end with heat loss. In contrast, other lighting sources such as incandescent bulbs and CFLs release 80% to 90% of their energy as heat (U.S. Department of Energy, 2018).

Some applications of LED are shown in Figure 2. Good discussions on the physics and design principles

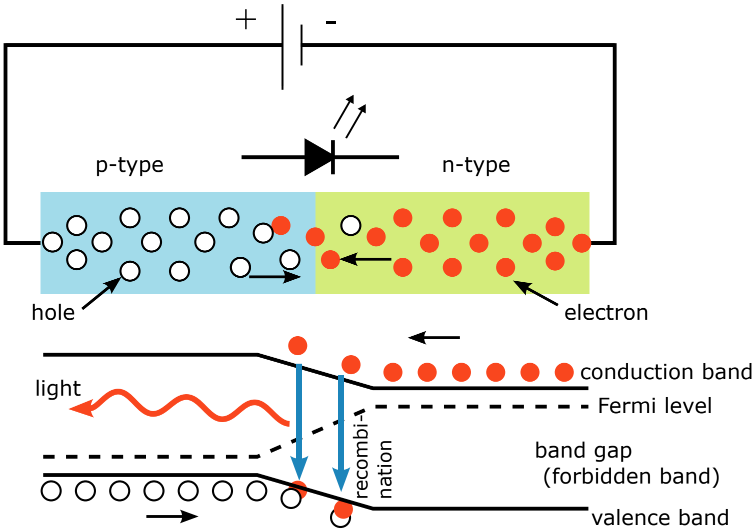

Figure 1: This demonstrates how LED works internally (Wikipedia contributors, 2018). The top part illustrates electrons and holes' recombination. The bottom part presents the 'band gap' between conduction band (higher) and valence band (lower).

of LED can be found in (Schubert, 2006).

(a) LED display on London Underground. (b) Used as daytime running lights on vehicle.

Figure 2: Use cases of LED (Wikipedia contributors, 2018).

2.2 GL

GravityLight®, or 'GL', is essentially a gravity-powered lamp. The product that is best known among public, was first developed in 2013 by London's Therefore Product Design Consultants (Brown, 2013), although similar ideas of using gravity to power LED had been proposed before that, for example 'Gravia' (Dunn, 2008).

GL is aimed at providing lighting solutions to people in developing communities who live without electricity. The product consists of a generator, LED, and drivetrain – eliminating batteries entirely. From an end user's point of view, all he/she needs to do is lifting about 20 pounds' weight to a certain height, then the drivetrain slows down the falling of the weight, during which process generator starts working and powering the LED (Figure 3). The current version is able to drive not only the main LED, but also two additional lamps (*SatLight*). The real illumination effects are pictured (Figure 4). Some of the major specifications are presented in Table 1.

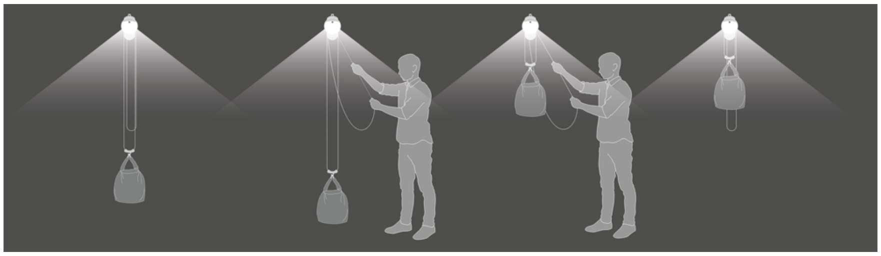

Figure 3: User lifts the bag (weight) to a certain height. Light is being created until bag reaches the ground (The GravityLight Foundation, 2018).

(a) Reading under *SatLight*.

(b) Main LED.

Figure 4: Deployment in southern Sri Lanka (Hamilton, 2014).

Table 1: GL Technical Specifications (The GravityLight Foundation, 2018)

Max loaded bag weight	12.5 kg
Max electrical power	0.085 W
Luminous flux	15 lm
Lighting time per 1.8m drop	20 mins
Weights falling velocity	1 mm/second
DC generator input rotation speed	1600 rpm

Considering conservation of energy,

$$\sum E_i + W_{\text{in}} = \sum E_f + W_{\text{out}} \tag{3}$$

where E_i and E_f are different types of energy the system contains at *initial* and *final* states, and W_{in} and W_{out} stand for work that is input into or output from the system.

In the case of GL, initially by having someone lift the weight to some height h_0, the system contains gravitational potential energy, $U_g(h_0)$. As weight gradually descends toward the ground and is finally stopped, the energy is partly transformed to do electrical work (W_{electric}) and is partly lost to friction/vibration/collision with ground, W_{lost}; the rest of the original energy E_{storage}, if any, can be stored for later use:

$$U_g(h_0) = E_{\text{storage}} + W_{\text{electric}} + W_{\text{lost}} \tag{4}$$

Equation 3 and Equation 4 serve as the basis for some analysis in later sections.

Since GL adopts LED in its system, it tries to maximize the lighting efficiency even only a small amount of potential energy can be leveraged. Compared to kerosene lamp, GL is obviously safer and healthier; it is also cheaper in the long run due to the fact it does not need any batteries.

3 A System Delivering Continuous Power

As shown from previous sections, GL is superior to traditional kerosene lighting in many ways. However, at current stage, it does come with an obvious limitation – the weight needs to be re-lifted every 20 minutes or so. The LED stops working as soon as the ‘stored’ gravitational potential energy is depleted. Therefore a natural question to ask is, are there any solutions to generate power continuously?

3.1 What does ‘continuous’ mean in the context?

When coming up with any solutions or products with potentials for deployment, the scope and the requirement need to be clarified. There are two levels of continuous power generation that can be pursued:

1. LED light is continuously working. In other words, when user pulls the rope lifting the weight (every 20 minutes), LED is always lighting the room with no interruptions.
2. Not only LED light, but also the whole power generation/conversion flow is continuous. In other words, some automation can be achieved and it works just like household electricity. Although it might need some type of ‘initialization’, for example pulling the weight only once at the beginning, the later power generation process is continuous.

For continuousness of the first kind, it is already achieved by the company that patented GL, by integrating a pulley system. The light stays on when user lifts the bag to 'recharge' the system, as long as the bag has not yet fully rested on ground (The GravityLight Foundation, 2018). In other words, there will be continuous lighting all night if user chooses to recharge (lift the bag to its starting position) a little more frequent than $\frac{1}{\text{20 mins}}$.

Achieving continuousness of the second kind is the focus of this discussion. It should be emphasized that perpetual motion machine is impossible in a closed system. Continuous power generation might be achieved with continuous energy supplement, or at least intermittently. However, the process can be treated as 'continuous' if the waiting time until next energy supplement is large enough. Taking GL as an example, if the bag needs to be lifted once a day for LED to continue lighting, the goal is achieved: the lighting needs is mainly for the nighttime and then household do not need to worry about recharging during each night. There are two directions for implementing such a system: energy storage and bringing in other forms of energy/work.

3.2 Energy storage

In this case, left-hand side for Equation 4 is held constant. It is assumed a fixed amount of gravitational potential energy is stored and to be used. Therefore, the following solutions are **not** considered here:

- Lift the weight to a higher elevation and let it fall into a wellbore which is drilled beforehand.
- Adopt mainspring/torsion spring as in pendulum clock, in which case additional (spring potential) energy can be stored by winding up the spring.

The design principle is to maximize E_{storage}, so that the waiting time until next round of recharging is maximized. From the domain of Electrical Engineering, battery and capacitor/supercapacitor can serve this kind of needs. They both can be used to store and retrieve electrical energy. On a high level, battery has higher capacity (energy storage), while capacitor excels at quicker response. In practice these two are often used together. This is also recommended for the system in this work.

The term W_{lost} is either to be minimized or to be converted into E_{storage} as much as possible. It is easy to understand dissipative work including work against friction is to be minimized. On the other hand, if that's not possible, try to convert those W_{lost} into E_{storage}. Ideally more electrical energy can be stored in battery/capacitor through solutions including:

- Use RSA (regenerative shock absorber) to harvest electricity from bag colliding with ground
- Use triboelectric nanogenerators to harvest electricity from friction

Lastly but importantly, for lighting to last longer using a certain amount of electrical energy, higher efficiency LED and corresponding circuit design should be adopted, i.e., to make the best use of W_{electric}.

3.3 Bring in other energy/work

In this case, options are considered for W_{in} from Equation 3. It is assumed that large scale wind farm, solar panel, or tidal power installation is not possible in this context (otherwise either of these would be desirable since it is solving problem on a larger scale instead of targeting individual families).

On a smaller scale, each household can leverage water wheel if possible. Energy of flowing water can be used to generate electricity, or to generate mechanical energy lifting the weight for GL. With the current setup of GL, it can also integrate small solar panels (as installed in calculators) from which more energy can be stored.

4 Evaluation of Proposed Solution

This section provides evaluation of the proposed system. This is a critical step before bringing any ideas into manufacturing/deployment stage, especially considering the size of the population that might be affected: as of year 2009, it was estimated that 1.5 billion people in the world have no access to electricity (Doll and Pachauri, 2010).

4.1 Technical Feasibility

The evaluation is focused on building an improved GL system (excluding for example the water wheel idea discussed in Section 3.3):

1. Including rechargeable battery and/or capacitor is technically ‘easy’ as these components are already adopted in some lighting solutions, for example mechanically powered flashlight.
2. Including high efficiency LEDs are also ‘straightforward’ at this day, since commercially available high efficiency products were already found around a decade ago; see (Huang-Jen Chiu et al., 2010) and (Krames et al., 2007).
3. Incorporating RSA and nanogenerators might be challenging as they have not been adopted in normal lighting solutions. Use of RSA has been mostly found in vehicles (Zhang et al., 2016), while research and development of triboelectric nanogenerators have been focused on harvesting energy from human motion (Bai et al., 2013).

Overall, the proposed system is technically feasible.

4.2 FMEA

FMEA stands for Failure Mode and Effects Analysis. Assuming good design principles being followed, i.e., good encapsulation and separation between different modules, FMEA is presented in Table 2.

Table 2: Failure Mode and Effects Analysis

Potential failure mode	Probability	Severity	Comments
Battery/capacitor failure	Remote[1]	Very minor	Fall back to current GL
LED failure	Remote	Critical	Core functionality
RSA/nanogenerators failure	Occasional[1]	Very minor	Fall back to current GL

4.3 Cost Considerations

Cost-wise, incorporating battery/capacitor and high efficiency LEDs are good options:

1. Battery and capacitor’s cost should be low enough as they are part of the majority of consumer electronics.
2. Cost of LEDs have decreased in recent years. Around a decade ago, LEDs are already cheaper than both incandescent bulbs and CFLs, when averaged out over their respective lifetimes (Pimputkar et al., 2009). Now, under Haitz’s law, which states that the cost per lumen for LED falls by a factor of 10 every decade, it is obvious how cheap it can be nowadays.

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[1] In probability ranking for FMEA, ‘Remote’ indicates relatively few failures, and ‘Occasional’ indicates occasional failures.

4.4 HSE

HSE stands for Health, Safety, and Environment. One of the reasons for replacing kerosene lamps with GL is for people to enjoy a healthier solution. This has to be re-evaluated for the proposed system as well. Again, the focus should be on high efficiency LEDs instead of battery/capacitor. A high efficiency incandescent-style organic LED is recommended for the new system, as it is 10 times safer for retinal protection and 4 times better for melatonin secretion (Jou et al., 2017).

5 Discussions

It is important to prototype. Borrowing ideas from agile development in software industry, when developing such a new system, small iterations/sprints shall be planned ahead. With the evaluation shown in Section 4, it is recommended to integrate battery/capacitor and higher efficiency LED as the first version. At a later stage, RSA and nanogenerators might be designed and added into the system.

There is always a trade-off between cost and functionality, as well as between reliability and complexity: the proposed system makes power generation more ‘continuous’, which is ‘better’ in that view. However, it costs more to build, and its reliability drops as system complexity increases.

To think out of the box, there could be a larger scale solution. The essence of GL technologies is gravity. One possible solution is to design a power generation and storage system as in Figure 5. During the time of peak electricity usage, the piston would be dropped and electricity is generated from gravity. With the help of solar/wind energy, the piston can be lifted at a later time. This should be used only when direct conversion of solar/wind energy into electricity is not possible or is of lower efficiency.

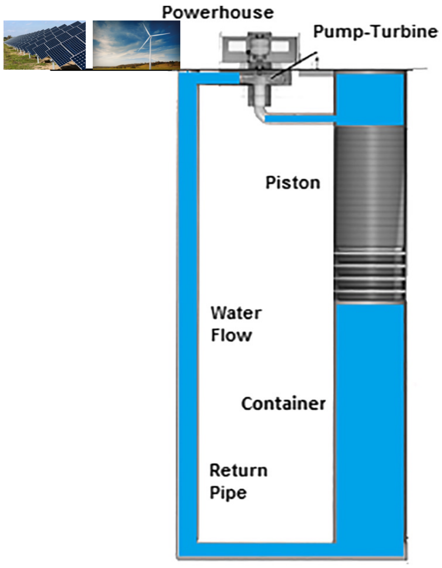

Figure 5: A gravity storage system with energy supplement from solar panels and wind turbines, adapted from (Berrada et al., 2017).

6 Conclusions

1. Reader should be reminded that perpetual motion machine is impossible. To design a continuous power (electricity) generation system, it is vital to design the energy flow (with the highest conversion efficiency), i.e., to clarify where the source energy comes from.
2. In the scope of powering GL for night use, the power generation can be treated as ‘continuous’ if waiting time between recharging is long enough. A potential method is proposed, leveraging energy storage and bringing in other sources of energy/work. More specifically, as a minimum viable product for this solution, it is recommended to integrate battery/capacitor and higher efficiency LEDs, to maximize the lighting time with one weight lift. Considering the current pulley system that is already developed, which makes lights on even during recharging, this new system will make household use GL more smoothly and effortlessly during each night.
3. The system is evaluated from different aspects and is shown to be feasible.
4. Any solutions that seem to function better in terms of continuous lighting, face the problem of costing more and having worse reliability, due to the increased complexity of system.
5. More innovations can be done and evaluated for powering the remote areas, especially new materials and new energy harvesting options.

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