Exploring Power Sources for Self Sufficient Robots via Inspiration from Nature

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***Abstract*— It makes sense to draw inspiration from nature to solve various challenges, including the problem of picking a suitable power source for a self-sufficient robot.**

As the investigation shows: Life on earth gains energy by either consuming fuel or absorbing electromagnetic irradiation or by spending internally contained resources. Robots could potentially do the same and each method has its benefits and drawbacks. Tables and graphs summarize the findings and aid in choosing an optimal solution by comparing them by energy/weight ratio, lifespan, price and environmental impact.

I. Introduction

Nature offers many insights on how to solve certain problems, yet human kind is still unaware of 86% of natural species [1]. Many places on earth are not comfortably accessible to human beings and pose various dangers to them either due to previous misguided human activity or due to naturally extreme environment – using robots for exploration could speed up data acquisition by a lot. A huge challenge when making robots for use in wilderness is the power source.

II. Power Source

It is very likely that centralized systems are not accessible in wilderness, so it is of topmost importance to figure out an energy source that does not depend on external supply of specialized fuel or other means to power it. Meaning, we need to have the robot be self-sufficient energy wise.

Nature offers multitude of options we can learn from. If we classify these possible power sources by their interaction type with the outside world, then they could be sorted into direct, indirect and internally contained (further explained below).

These three are directly nature inspired and thus logical - we use different materials to achieve the same effect out of both convenience and our lack of understanding about biological mechanisms. Which is not necessarily a flaw – using a different approach can lead to different uses.

The energy part itself includes gathering (absorbing) and storage of energy. If a device if capable of these two, then it already is energetically self-sufficient. Since it is not yet known how much energy will be needed, it might be wise to look over all the commonly used technologies, which might be used in the wild, assuming that it is not possible to get conventional fuel or there is no time and resources to prepare reservoirs of possible fuel.

A. Direct

Consumption of some sort of fuel to gain energy. Most living creatures do that by feeding on organic or inorganic matter and extracting energy from it. For example, humans (homo sapiens) feed on organic matter, while many archaebacteria, like Methanothermus fervidus and ferroglobus placidus, consume inorganic matter like carbon dioxide and iron [2].

The biggest problem with this energy source is waste, impurities in the fuel and moving details - that all makes this power source messy and prone to wear. In addition, it requires a high level of intelligence or a hit and run strategy to discern and collect the fuel. That is displayed by the high complexity of instinct and sensory organs of humans and other mammals – human ability to see color and taste preference for food richer in calories or certain nutrients, disgust they feel when smelling rotten meat, developed reflex to avoid food that has once brought them harm [3]. The other strategy is illustrated by the amount of spores fungi spread out until a source of food is found. The success rate for finding a food source and perfect growth conditions is low, so fungi make up with quantity [4].

The best part about this power source is the high density of power that can be extracted and often the variety of minerals and other nutrients that help maintaining a complex biological mechanism such as human bodies.

The bits above only fully apply to biological mechanisms, humans cannot exactly replicate that yet, but the known technology to convert biomass into useful energy is combustion. Gasification, pyrolysis, torrefaction and fermentation are merely means to make more efficient fuel from biomass [5].

In its natural state most of biomass is very rich in moisture, even peat has a moisture content of 85-95% [6], while freshly cut wood has one ranging from 45% to 75% [7].

Combustion or oxidation of biomass with a moisture content like that is not easy – it requires heating up the biomass until it is dry, then burning the carbons in it to get heat. Then this said energy of heat could drive a turbine and move the mechanism or be transformed into electricity thermoelectrically - preferably combined, as electronics need a supply of direct current, while movement can be powered in various ways.

There are certain challenges and considerations in this option – how will the robot gather this biomass? What is the efficiency of the process? Would the robot need some extra energy source to trigger the process – getting the mass to burn at all? Open air combustion is only 5% efficient, while some ovens are said to be 117% efficient (taking into account both the energy of heat and electrical energy) [5]. However, most of the data available is assuming that the fuel is dry.

Using combustion, it’s possible to get 4 Wh/g from dry wood [8] and 6 Wh/g [9] from dry peat. The quantity of energy required to remove water depends on temperature and pressure of the system usually between 0.52 to 0.7 Wh/g [10].

This leads to average fuel efficiency of peat being at least 5 Wh/g if it's gathered from nature and a range of 2.5 to 3.5 Wh/g for wood. Efficiency of combustion if it's meant to be transformed into motion is that of about 20%, same as animal muscle efficiency for propelling movement, rest is heat [11]. Thermoelectric cells are about 5% efficient when it comes to transforming heat into direct current, but could reach 15-20% [12].

It is questionable if the efficiencies above justify the need to employ a complex fuel gathering and combustion system: that most likely depends on availability of other options.

B. Indirect

Absorbing some sort of energy wirelessly - usually it is the absorption of electromagnetic irradiation and chemically transforming this energy into something else. Photosynthesis is the most common example [13], radioactive mushrooms is another [14].

The biggest problem with this energy source is low energy density in irradiation and constant need for availability of sunlight, best part is no need for moving details and minimal or no waste in energy production stage.

Both in natural structures and manufactured the benefits remain the same. Artificial photosynthesis is possible, yet the main value in it is production of hydrogen, which can be later used as fuel. That is one method to gain energy from sunlight. However, thus far there have been no commercially available technologies using this principle, thus it remains 'a future' solution. The biggest problem so far is the short lifetime of the sensitizer or/and low efficiency [15].

Semiconductors, however, offer to directly transform light quanta into electric current in photovoltaic conversion. Photosynthesis in nature is only up to 2% efficient [16], while the top efficiency research photovoltaic cell under regular light is 38.8% efficiency [17]. Of course, this is by no means an attempt to undervalue the effect photosynthesis has on our world – without it human life on earth would not be possible and a huge part of human diet comes from plants, who use the said photosynthesis to propel their growth. Although it does point out how amazing photovoltaic cells can be: 38.8% efficiency translates to 388 W of energy per square meter under direct sunlight in 1.5 AM atmospheric conditions.

The two options above offer the possibility to extract energy from direct irradiation from sunlight, however it would not be right to forget the indirect source of energy that comes from it, which is wind. While it might not be easy to use wind turbines on autonomous robots, Theo Jansen's kinematic sculptures illustrate that it is possible to propel the movement of autonomous mechanisms using wind [18]. However, relying on this type of energy source might not be feasible in places where there isn't a frequent and reliable amount of air flow.

C. Internally Contained

Being born with the whole necessary energy amount for life. It's typical in mayflies at the adult stage of their life - after reproducing they tend to die as they are physically incapable of gathering more energy [19].

The biggest problem with this energy source is the short lifespan, finality, best part is no need for moving details, and since the system is self-contained, there is no waste in energy production stage. The possible power output varies, but is comparable with the one biologically gained from food consumption.

While man-made structures using this principle, such as primary batteries and radioisotope thermoelectric generator, do have the issue of finality, short lifespan is not necessarily the case. Possessing all necessary energy amount for life means it already has the fuel needed to perform a certain amount of functions and it does not depend on external factors. Moreover, there are all kinds of fuel out there.

While using cellular respiration human bodies can extract 7 Wh/g from fats and 10.5 Wh/g from natural oils [20] (and those are the richest fuels in natural world). One gram of plutonium 238 isotope is capable of releasing 0.557 Joules of heat energy each second (0.557 W), and that halves in 87.74 years [21]. To compare – in a day those would be 4812 Wh/g.

Of course, the extraction speed of the said energy also plays a role and so does our ability to harness this energy. While the figure of almost five thousand Watthours per gram might seem mind-blowing - that is thermal energy. Current ability to get current from thermal energy via thermoelectric conversion is at around 7% in Radioisotope Thermoelectric Generator [21] and around 26% in Advanced Stirling Radioisotope Generator [22]. While heat is also an important resource and might help in keeping the rest of the system in its optimal temperature, excessive amounts lead to necessity to cool the system.

More common than radioisotope generators, there are power sources extracting energy from chemical redox reactions – primary batteries. Lithium battery is the top efficiency primary cell capable of delivering around 0.3 Wh/g in electric current currently and some technologies are predicted to reach 1 Wh/g after overcoming several fundamental challenges [23]. However, it is rather clear that this amount is insufficient for the considered use.

D. Summary

To summarize, the tables below cover the information about possibly useful energy sources and the tools to convert this energy for immediate use and storage.

TABLE I

POTENTIAL ENERGY SOURCES

Energy source	Main parameters	
	Energy type	Energy amount per weight unit.
Biomass	Fuel	Up to 5 Wh/g,[#]
Sunlight	Electromagnetic irradiation	In Latvia around 1000 kWh/m2 in a year [25]
Radioactive isotopes	Heat	Plutonium 238 – 0.557 W/g Half-life – 87.74 years [21] SrTiO3 – 0.223 W/g Half-life – 27.7 years [26] Americium 241 – 0.114 W/g Half-life – 423.6 years [21][*]

[#] - Number concluded from literature sources 6, 9 and 10 by reasoning provided in the text above.

[*] - Radioactive isotopes continuously emit the said energy amount, yet it gradually drops by half once the isotope has reached its half-life.

TABLE II

ENERGY CONVERSION TOOLS

Type	Main parameters		
	Energy type	Conversion efficiency	Power/weight
Boiler/Oven	Fuel to heat	65-75%[27]	Around 400 kg for 20 kW of heat [28]
Steam engine	Heat to mechanical movement	31.5% in one recent steam engine [29]	Around 160 kg for a 100 HP (75 kW) engine [29] 470 W/kg
Stirling engine	Heat to mechanical movement	Existing engines reach 40% at best [30]	Around 300 W/kg [31]
Thermoelectrical cells	Heat to DC	5-7% [32]	7.9 W/kg [32]
Solar cells	Sunlight to DC	Up to 38.8% [17]	Up to 210 W/kg [33]
RTG	Heat to DC	6.5-7% [21]	5.2 W/kg [21]
ASRG	Heat to AC	26% [22]	4.1 W/kg [22]

Note: RTG – Radioisotope thermoelectric generator, ASRG – Advanced Stirling Radioisotope Generator. Both RTG and ASRG contain the needed fuel, Solar cells absorb irradiation which does not add to weight. Other types of conversion tools need fuel.

TABLE III

ENERGY STORAGE

Type	Main parameters		
	Energy type	Conversion efficiency	Power/weight
Accumulators	Electrochemical	Up to 85% [34]	Up to 250 Wh/kg [24]
Supercapacitors (Ultracapacitors)	Electrochemical	Up to 98% [34]	Up to 10 Wh/kg [24]

It's important to note, that electrochemical secondary batteries (accumulators) and supercapacitors are mostly used together, since – supercapacitors are capable of delivering a huge amount of power instantly (around 85% of its total charge), while accumulators supply a stable amount over a longer time period. Supercapacitors also happen to have a longer lifespan [24].

III. CHOICE VARIABLES

The choice of a power source is always multidimensional by no means easy; each type does have their own benefits as well as drawbacks. When making the choice between them the main considerations could be lifespan, power/weight ratio, cost and environmental impact.

A. Lifespan

If a look is taken at the open literature available, then RTGs are designed for 1-5 years of operation, but usually far outlive this estimate, Voyager 1&2 RTG is operating over 30 years [35]. The high efficiency solar cells are designed to work up to 20 years in outer space [33], regular terrestrial use solar cells are designed for up to 25 years, even if their efficiency (and also price) is considerably smaller at 21.5% [36]. Nowadays Stirling engines are efficiently used to power silent submarines. Considering they can be built hermetically closed, they have long lifespans, currently working samples go over 7 years of continuous operation [37], while automotive uses were shelved back in 80's, due to lack of interest from car producers, despite showing promise [38]. Steam engines and Boilers/Ovens are solutions that require frequent maintenance, without any it is expected that the device will stop working before two years have passed due to some part failing [39].

Thus, if the energy sources are compared by their lifespan, then it would show up as the graph below. Due to lack of data for abandoned or not maintained devices in most part, it is assumed that the chance of failure at each passing year is 1/8 for an unmaintained Stirling engine after average warranty (2 years) and 1/4 of an unmaintained boiler/oven/steam engine after average warranty (1 year) is over, these probabilities are assumed considering recommended maintenance intensities. For solar panels, as they have no moving details, maintenance itself or cleaning of the surface is only needed if they are located in a place with insufficient rainfall to naturally wash them, so it depends. No data about ASRG lifespan in use was found.

Of course, the graph (see fig.1) only vaguely illustrates the life expectancy of the power sources themselves, two of whom do not have moving details that would be intensely prone to wear.

B. Energy Density

Power weight ratio from the tables above shows up as the following charts (see fig. 3 and 4).

Each robotic technology is limited by its maximal cost of transport (COT), for example, airborne robots or drones would be able to carry far less weight than crawlers or swimmers, thus it helps to compare.

C. Price

Currently, the selling price for stirling engines varies from 2000$/kW to 36000 $/kW, it is predicted that the price would fall to 1000$/kW [40]. High efficiency solar cells cost around 250-400$ per watt, according to their producer Boeing [41]. While the exact cost of RTG is not disclosed, one gram of plutonium 238 costs 4000$ [42], considering the efficiency of thermoelectric cells ($\eta_{Th)}$ being around 6%, to get one Watt of power from RTG would take around 30 grams, as seen in equation 1:

$$1/(P_{Pu238} * \eta_{Th.}) = 1/(0.557*0.06) = 29.9g. \quad (1)$$

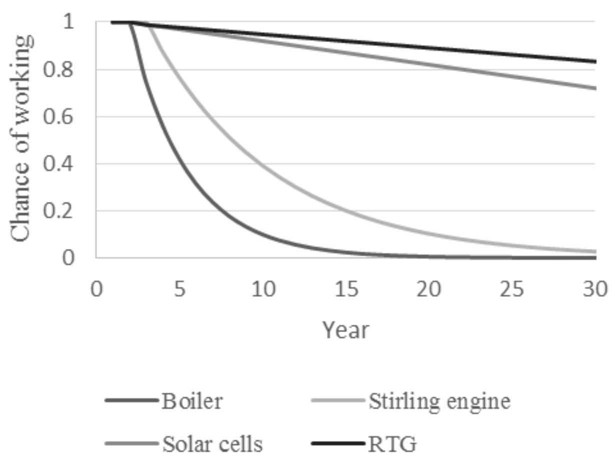

Fig. 1. Lifespan of the power source itself. It is assumed that maintenance is not available, thus power sources with exposed parts have a deterioration coefficient applied.

And around 30 grams of Pu_{238} would cost at least 4000*30=120000$, means that one watt of power from RTG would cost more than 120 000$. And considering that the efficiency of ASRG is higher, more than 28000$ from an ASRG.

The price of Cyclone Steam Engine (with the 31.5% efficiency) is not disclosed. Steam based power plants tend to cost at around 4 000 $/kW [43]. Might be a rough estimate, yet considering that most of these things are a corporate secret, it is not easy to put a price tag on them.

Boilers and ovens are the most commonly used sources of heat. The technology itself being so commonplace it might be the easiest to build and thus there is plenty of competition to drive the prices down. Biomass burning boilers and ovens tend to cost around 50 000$ for 50 kW device [44].

Fig.3 and 4 show the comparison of the said prices if the price estimate is divided by the nominal power the said device can deliver. Of course, this comparison is rough and should not be taken literarily, as not all technologies are easily made smaller or bigger and their efficiencies can change depending on their size. Yet the figures do tell about the relative cost comparison to aid in choosing an appropriate one.

D. Environmental Impact

Yet monetary worth is not the only price a device has.

It is apparent that there is a shift taking place in the general populace when it comes to value of preserving environment due to raising standard of life – movement towards organic food, raising concerns about carbon footprint, growing requirements for safer and cleaner technologies, as humans are slowly growing aware of the fact that cleaner environment leads to better health and possibly longer life. It has little to do with altruism and everything to do with the basic fear of painful death.

Boilers, Ovens, Steam engines commonly share the issue of greenhouse gas emissions, since they do burn biomass or fuel to get the needed heat.

Stirling engine itself needs heat to operate, if it is gained by burning biomass, then the issue is the same as with before mentioned three.

High efficiency solar cells do not emit greenhouse gasses, yet they do contain toxic materials – indium and arsenic [33].

Radioisotope generators (RTG and ASRG) both have the question of radioactivity hanging over them thus using them for terrestrial use might have the biggest resistance, unless there is no other option available [45].

There is hope that with developments in the area solar cells might become even greener [46] and filtering out the greenhouse gasses is a possibility, thus radioisotope generators might have the hardest time with social acceptance.

IV. Discussion

As seen in the chapters before each type of power source has its benefits and drawbacks – both in natural biomechanisms and human developed technologies alike. Interesting enough, the only type of power source that beats its natural equivalent is internally contained if radioisotope generators are used – in that sense – man has beaten nature. Solar cells are also more efficient than plants are at converting light to energy, yet that is also because of how one dimensional and scalable our technologies are when compared to evolution driven organisms. Evolution does not favor high specialization as much as we do: without flexibility – extinction becomes far more likely. Yet that also makes human creations as entertaining as they are – they do tell very much of how we are prone to think at least in this stage of our technological development.

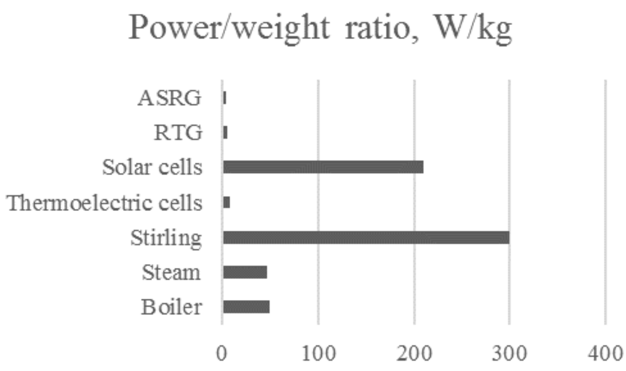

Fig. 2. Comparison of power sources by their power/weight ratios. It is important to consider that only ASRG, RTG and Solar cells include ‘fuel’ in their weight.

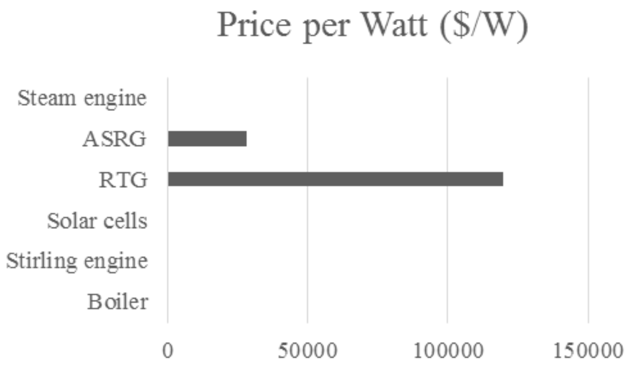

Fig. 3. Comparison of cost estimates. Considering the price league of radioisotope technologies is way higher than other technologies, other types do not even ‘appear’. Important to note that Radioisotope technologies already contain the needed fuel.

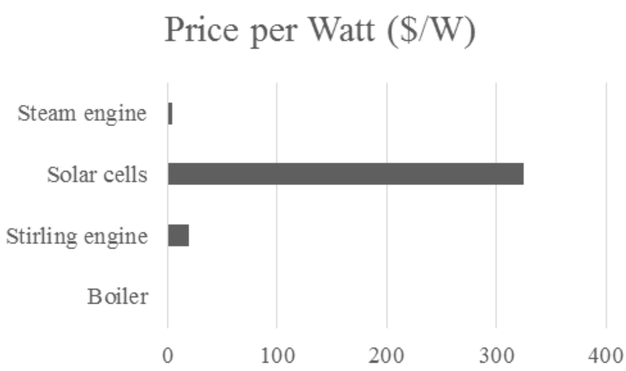

Fig. 4. Comparison of cost estimates excluding radioisotope technologies. Solar cells do not require additional costs for fuel in operation, so while their price is high upon purchase, to fully compare them to other sources, it is important to consider the cost of operation (not included in this chart).

V. CONCLUSIONS

Information on various manmade power sources has been compiled and sorted in parallel with how nature solves the need for energy in its creations. The said energy sources have been compared by their lifespan, price, energy density and environmental impact, painting a picture of what the benefits and drawbacks are when it comes to using them.

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