Energy-Investment Schemes for Increasing Output Power in Piezoelectric Harvesters

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***Abstract*—Energy and power in tiny batteries are often insufficient to sustain the demands of a wireless microsystem for extended periods. Piezoelectric transducers are viable alternatives because they draw power from a vast tank-free supply of ambient kinetic energy in vibrations. Unfortunately, small devices alone seldom dampen vibrations enough to fully harness what is available, which is why investing energy to increase the electrical damping force that transducers impose is so important. This paper introduces and evaluates three investment schemes and 0.35-µm CMOS switched-inductor circuits that increase this force to generate more output power.**

I. Harvesting Piezoelectric Energy

Miniaturized *in-situ* electronic devices, such as wireless microsensors [1] and tiny biomedical implants [2], can monitor and process information non-intrusively to add intelligence to otherwise inaccessible environments. Tiny batteries, however, limit energy and power, so lifetime is often short and functionality is low. Luckily, a harvester needs no tank to store ambient energy, so extending the lifetime and expanding the functionality of a tiny device is possible [3]–[4]. In this regard, piezoelectric harvesters enjoy popularity [5]–[6] because they produce moderate power levels with relatively mature and robust technologies [7].

Fundamentally, a piezoelectric transducer, as Fig. 1a shows, converts mechanical energy E_{ME} into the electrical domain E_{PZ} internally. In essence, motion produces and steers charge into an internal capacitor that C_{PZ} in Fig. 1b models [8]. Although not much, some of the alternating current i_{PZ} that vibrations generate leaks through what Fig. 1b models as R_{LEAK}. Irrespective of this, C_{PZ}'s energy peaks when its voltage v_{PZ} peaks, so the system can harvest the most energy at $v_{PZ(PK)}$:

$$E_{PZ} = q_{PZ} v_{PZ} \le 0.5 C_{PZ} {v_{PZ(PK)}}^2 = E_{PZ(PK)} . \quad (1)$$

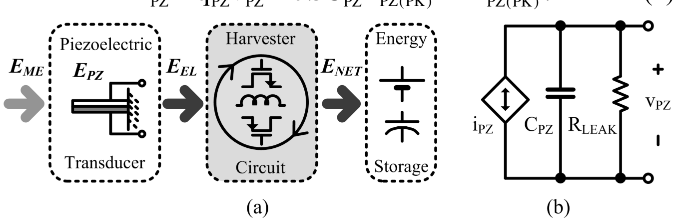

Fig. 1. (a) Harvester system and (b) piezoelectric transducer's circuit model.

Micro-scale structures, however, bend little and couple little mechanical to electrical energy [9], so they capture a fraction of the energy available. Fortunately, increasing the electrical damping energy in the transducer, as Section II describes, conditions the device so it can extract more energy [10]. Sections III – V therefore introduce harvester systems that re-invest and/or invest energy for this purpose, Section VI compares the schemes, and Section VII draws conclusions.

II. Investing Energy to Increase Electrical Damping

In drawing energy from motion, a transducer ultimately dampens vibrations. As a result, boosting the damping force further opposes vibrations to draw more energy as long as this force is below a threshold beyond which vibrations would otherwise desist [9]. The coupling factor k_C of a tiny device is so low, however, that over-damping the system with electrical energy is rarely possible [10]. In other words, increasing the electrical damping force in miniaturized harvesters typically raises output power in monotonic fashion.

In the case of piezoelectric transducers, the electrostatic energy in C_{PZ} (from Fig. 1b) establishes the electrical damping force against which vibrations work to generate power. As such, depositing more energy into C_{PZ} further dampens the system to draw more power. To quantify this, consider that, because k_C is so low, v_{PZ} rises and falls Δv_{PZ} independently of what initial voltage C_{PZ} has across its plates. So, pre-charging C_{PZ} to V_{PC} with energy E_{PC} and allowing vibrations to raise v_{PZ} further to $V_{PC} + \Delta v_{PZ}$ raises $v_{PZ(PK)}$ linearly and $E_{PZ(PK)}$ quadratically to such an extent that output electrical energy E_{EL} (after discounting E_{PC}) is greater with V_{PC} than without:

$$E_{EL} = E_{PZ(PK)} - E_{PC} = 0.5 C_{PZ} \left[\left(V_{PC} + \Delta v_{PZ} \right)^2 - {V_{PC}}^2 \right]$$
$$= 0.5 C_{PZ} \left({\Delta v_{PZ}}^2 + 2 V_{PC} \Delta v_{PZ} \right). \quad (2)$$

This means that investing E_{PC} raises E_{EL} as long as E_{PC} does not over-damp vibrations, which is unlikely in microsystems.

Because conditioning electronics in Fig. 1a consume power, how harvesters harness energy and derive E_{PC} determines how much power the system can generate. Although diode-bridge rectifiers can harness and invest energy into C_{PZ}, they draw power *only* when C_{PZ}'s v_{PZ} rises above C_{PZ}'s rectified output [11]–[12], even when diode voltages are zero. Switched-inductor harvesters overcome this fundamental limitation because inductors draw energy from infinitesimally small non-zero voltages [13]. In this context, because power inductors are normally bulky and portable and non-intrusive applications demand low form factors, single-inductor converters generally outmatch their multiple-inductor counterparts [14]. Still, how and what source should supply E_{PC} remains a question.

III. Re-Investing Harvested Energy

A means of deriving pre-charge energy E_{PC} for C_{PZ} is by subtracting it from harvested energy E_H, as Fig. 2 shows. Re-investing energy this way is only possible, though, when E_H is greater than E_{PC}, which means the net difference can charge a battery V_{BAT}. For this, a switched inductor L_H waits until v_{PZ} peaks before temporarily draining and drawing C_{PZ}'s $E_{PZ(PK)}$. L_H then recycles a portion of $E_{PZ(PK)}$ back into C_{PZ} to pre-charge C_{PZ} in the opposite direction (for the ensuing half cycle) and uses the remainder to charge V_{BAT}. Note that, because vibrations normally oscillate at 50 – 300 Hz [3] and transferring energy to and from L_H requires μs of the ms period, the re-investment process is practically instantaneous.

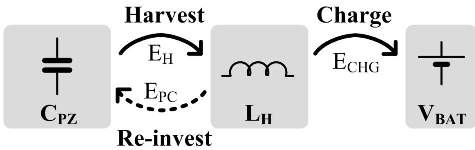

Fig. 2. Energy-flow graph for re-investing harvested energy back into C_{PZ}.

The switched-inductor circuit proposed in Fig. 3a implements the energy flow shown in Fig. 2. Here, S_C opens to allow vibrations to charge C_{PZ} (with i_{PZ}) until v_{PZ} peaks at V_{OC}, at which point (from Fig. 3b) S_C closes to drain C_{PZ} into L_H. C_{PZ} fully depletes after a quarter of L_HC_{PZ}'s resonance period $0.25T_{LC}$. Since over-damping vibrations is rarely possible in micro-scale applications, re-investing all this energy back into C_{PZ} produces higher gains. As a result, S_C closes long enough (after another $0.25T_{LC}$) to re-cycle all of L_H's energy back into C_{PZ}. S_C then opens to allow vibrations to charge C_{PZ} further in the negative direction. When v_{PZ} reaches its negative peak, S_C closes again, but only for $0.25T_{LC}$, so that L_H receives and retains all of C_{PZ}'s energy. Immediately opening S_C after that steers L_H's current i_L through diode D_B into V_{BAT} until i_L drops to zero, at which point the vibration cycle ends.

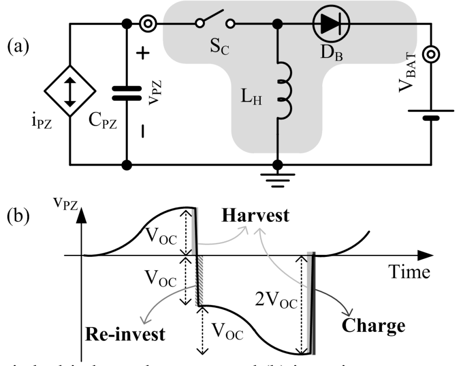

Fig. 3. (a) Switched-inductor harvester and (b) its re-investment waveforms.

If vibrations are reliable and consistent, S_C can remain closed another $0.25T_{LC}$ to re-deposit L_H's energy back into C_{PZ}, rather than charge V_{BAT}. In other words, the circuit can re-invest all the energy it harvests across several cycles to continually raise the electrostatic force (i.e., v_{PZ}) against which motion works to generate power. This way, the circuit harvests an increasing amount of energy until voltages reach the breakdown limits of the switches; conduction losses, which increase with input power, overwhelm energy gains; or the force over-damps (i.e., stops) vibrations [10]. Unfortunately, ambient vibrations are mostly inconsistent, and typically, the result of irregular collisions, like when a falling object hits the ground, so single-cycle charges are typically more suitable.

As such, since the circuit re-deposits the energy required to charge C_{PZ} to V_{OC} in the positive half cycle back into C_{PZ}, C_{PZ} pre-charges to $-V_{OC}$ before the negative half cycle begins. The harvester then allows motion to charge C_{PZ} further another V_{OC} to $-2V_{OC}$, before finally draining C_{PZ} fully into V_{BAT}. This means the system ultimately draws C_{PZ}'s energy at $-2V_{OC}$:

$$E_{NET} = E_H^+ - E_{PC} + E_H^- = 0.5C_{PZ}\left(2V_{OC}\right)^2 = 2C_{PZ}V_{OC}^2. \quad (3)$$

IV. Investing Battery Energy

One drawback to re-investing energy is that harvested energy (E_H) alone may not establish sufficient electrical damping. Deriving energy from the battery V_{BAT}, rather than from E_H, overcomes this limitation. For this, the system first invests pre-charge energy E_{PC} into L_H and then, as Fig. 4 illustrates, transfers it from L_H to C_{PZ}. Vibrations subsequently work against C_{PZ}'s electrostatic force to supply energy into C_{PZ} until C_{PZ} peaks, at which point the circuit harnesses C_{PZ}'s energy E_H into L_H so L_H can use it to charge V_{BAT}.

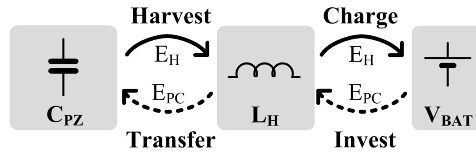

Fig. 4. Energy-flow graph for investing battery energy into C_{PZ}.

The switched-inductor circuit proposed in Fig. 5a derives E_{PC} from V_{BAT} like Fig. 4 describes. For this, S_{B1} and S_{X1} first close to energize L_H with E_{PC} from V_{BAT}. S_C and S_{X2} then engage for $0.25T_{LC}$ to transfer L_H's E_{PC} to C_{PZ}. After pre-charging C_{PZ} to V_{PC}, vibrations charge C_{PZ} further by another V_{OC} across the positive half cycle of the vibration period, as Fig. 5b shows. S_C and S_{X2} then close for $0.25T_{LC}$ to drain C_{PZ} into L_H, after which S_{B1} and S_{X1} engage to channel L_H's i_L into V_{BAT} until L_H depletes, completing the harvest and charge phases of Fig. 4. The circuit then follows a similar sequence across the negative half cycle: S_{B2} and S_{X2} invest E_{PC} into L_H, S_C and S_{X2} transfer E_{PC} to C_{PZ} to pre-charge C_{PZ} to $-V_{PC}$, vibrations charge C_{PZ} further to $-(V_{PC} + V_{OC})$, S_C and S_{X2} drain C_{PZ} into L_H, and S_{B2} and S_{X2} empty L_H into V_{BAT}. Since V_{BAT} invests E_{PC} to pre-charge C_{PZ} to V_{PC} and draws C_{PZ}'s E_H at $V_{PC} + V_{OC}$ twice per cycle, V_{BAT} gains $E_H - E_{PC}$ twice per cycle:

$$E_{NET} = 2\left(E_H - E_{PC}\right) = 2\left(0.5C_{PZ}\right)\left[\left(V_{PC}+V_{OC}\right)^2 - V_{PC}^2\right] = C_{PZ}\left(V_{OC}^2 + 2V_{PC}V_{OC}\right). \quad (4)$$

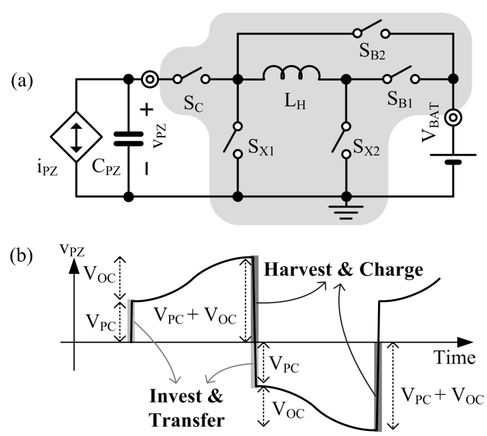

Fig. 5. (a) Switched-inductor harvester and (b) its investment waveforms.

V. Re-investing and Investing Energy

Another way of supplying enough pre-charge energy E_{PC} to C_{PZ} when harvested energy E_H alone is insufficient is by supplementing (not replacing) E_H with energy from V_{BAT}. In other words, like Fig. 6 shows, the system can drain C_{PZ}'s E_H^+

from the positive half cycle into L_H and re-invest all of E_H^+ back into C_{PZ} to partially pre-charge C_{PZ} in the opposite direction. The harvester can then invest E_I from V_{BAT} into L_H and transfer L_H's E_I into C_{PZ} to finish pre-charging C_{PZ} to $-V_{PC}$. After the negative half cycle further charges C_{PZ} to $-(V_{PC} + V_{OC})$, the system charges V_{BAT} with C_{PZ}'s energy E_H^-.

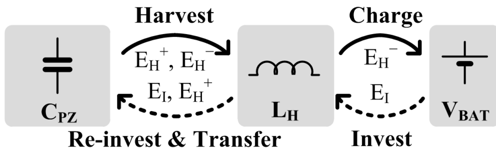

Fig. 6. Energy-flow graph for re-investing and investing energy into C_{PZ}.

Like Fig. 6 prescribes, the switched-inductor circuit proposed in Fig. 7a derives pre-charge energy by both re-investing harvested energy and investing battery energy. The difference between this converter and the re-investment-only counterpart of Fig. 3a is that this one replaces unidirectional diode D_B with a bi-directional MOS switch (S_B). This way, L_H can not only charge V_{BAT} but also draw energy from V_{BAT}.

From an operational perspective, as Fig. 7b shows, motion charges C_{PZ} to V_{OC} across the positive half cycle. S_B then closes momentarily (across time T_I) to energize L_H from V_{BAT} with investment energy E_I. Next, S_C engages to further energize L_H with C_{PZ}'s harvested energy E_H^+ and remains closed to deposit both E_I and E_H^+ into C_{PZ}, which together pre-charge C_{PZ} to $-V_{PC}$. After that, motion charges C_{PZ} across the negative half cycle until C_{PZ} peaks at $-(V_{PC} + V_{OC})$, which is when S_C engages for $0.25T_{LC}$ to drain C_{PZ}'s energy into L_H and S_B then closes to deplete L_H into V_{BAT} (until i_L falls to zero).

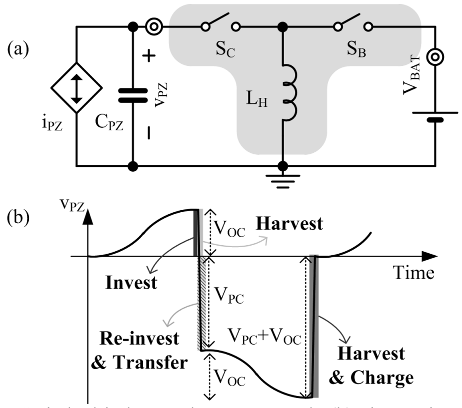

Fig. 7. (a) Switched-inductor harvester and (b) its re-investment and investment waveforms.

Note that either the user or the system (via a slow negative-feedback control loop) should tune T_I to ensure L_H energizes with just enough energy to fully supplement C_{PZ}'s E_H^+. As such, E_I and E_H^+ together supply pre-charge energy E_{PC}:

$$E_H^+ + E_I = E_{PC} = 0.5C_{PZ}V_{PC}^2. \quad (5)$$

At the end of the cycle, V_{BAT} receives C_{PZ}'s energy at $-(V_{PC} + V_{OC})$, which means V_{BAT} charges with

$$E_{CHG} = E_H^- = 0.5C_{PZ}\left(V_{PC}+V_{OC}\right)^2. \quad (6)$$

In other words, after discounting investment E_I, V_{BAT} gains

$$E_{NET} = E_H^+ - E_{PC} + E_H^- = 0.5C_{PZ}\left[V_{OC}^2 - V_{PC}^2 + \left(V_{PC}+V_{OC}\right)^2\right] = C_{PZ}\left(V_{OC}^2 + V_{OC}V_{PC}\right). \quad (7)$$

VI. Evaluation and Comparison

Damping: Irrespective of the electronics used and investment scheme adopted, there is an optimal electrostatic damping force (i.e., pre-charge voltage V_{PC}) with which to draw the most power from a vibrating piezoelectric transducer. As such, optimally damping the transducer every half cycle (by pre-charging C_{PZ} to V_{PC} at the beginning of the positive half cycle and then to $-V_{PC}$ at the onset of the opposite half cycle) generates the most power. This is why E_{NET} from the circuit of Fig. 5a and waveforms of Fig. 5b is fundamentally higher (by $V_{OC}V_{PC}$) than Fig. 7's counterpart, because the latter only optimally damps the transducer in the negative half cycle.

Ultimately, however, breakdown voltage limits how much the harvester can damp the transducer. In Fig. 5, for example, v_{PZ} falls to $-(V_{PC} + V_{OC})$ and rises to $V_{PC} + V_{OC}$, so to damp both positive and negative half cycles, the switches must survive $2(V_{PC} + V_{OC})$. Since v_{PZ} in Fig. 7 increases only to V_{OC} and drops to $-(V_{PC} + V_{OC})$, the switches need only endure $2V_{OC} + V_{PC}$. In other words, given that over-damping microsystems is often impossible, comparing schemes without normalizing voltage swings across C_{PZ} is unfair.

Power Losses: Parasitic power losses across a circuit also play a pivotal role in harvesters, especially in micro-scale applications where output power is on the order of microwatts. From this perspective, since every energy transfer incurs power losses, eliminating unnecessary and redundant transfers across a system is crucial. Similarly, because losses increase with how much power L_H conducts, minimizing the amount of energy transferred in each transaction is also imperative.

Comparison: Since breakdown voltage ultimately limits how much damping is possible, a fair comparison of energy-investment schemes should normalize v_{PZ}'s maximum swing. Said differently, the total damping across a vibration period, whether it is in the positive or negative direction, or both, should be the same in all cases. With this premise, comparing investment strategies amounts to comparing transfer losses.

Ultimately, battery energy in miniaturized sensors is harvested energy already transferred into the battery. This means investing battery energy fundamentally requires more transfers and carries more energy in one or more of the transfers than re-investing harvested energy E_H. Re-investing E_H in Fig. 3, for instance, requires three transactions: Harvest, Re-invest, and Charge, while investing battery energy in Fig. 4 needs four: Harvest, Charge, Invest, and Transfer. Plus, Charge in Fig. 3 transfers less energy (at $E_H - E_{PC}$) than Charge in Fig. 4 (at E_H). Therefore, when E_H is sufficiently high to optimally damp vibrations, re-investing E_H generates the most power.

Optimal damping, however, typically has more impact on output power than transfer losses. So, when E_H is not sufficient, the gains that result from supplementing E_H with battery energy outweigh the transfer losses of the investment process. Still, re-investing all of E_H reduces how much energy the system transfers from the battery into C_{PZ}, so re-investing E_H *and* investing battery energy produce more power than investing battery energy alone. In comparing Figs. 4 and 6, for example, the Charge and Invest phases in the latter transfer less energy (at E_H^- and $E_{PC} - E_H^+$, respectively) than in the former (at $E_H^- + E_H^+$ and E_{PC}), so the latter loses less power.

Validation: SPICE simulations of the single-inductor circuits proposed in Figs. 3a, 5a, and 7a verified the aforementioned assertions. For fairness and consistency, the simulations emulated TSMC's 0.35-μm MOS switches and normalized silicon real estate so that the total area in all three cases was equal. Channel lengths were 1.5 μm because 15-V devices require as much and channel widths, as selected and shown in Table I, balanced conduction and gate-drive losses to the extent that equal overall areas allowed. C_{PZ} and L_H, which are off chip, were 20 nF and 100 μH. Because breakdown voltage is an external factor that limits damping, v_{PZ}'s maximum swings were consistent at 15 V in all cases.

TABLE I. EMULATED 15-V CMOS SWITCHES.

Re-invest (Fig. 3a) & Combined (Fig. 7a)	S_C	NMOS	W / L	30,000 μm / 1.5 μm
			R_{ON}	0.78 Ω
			C_G	51.8 pF
	S_B (D_B)	PMOS	W / L	80,000 μm / 1.5 μm
			R_{ON}	1.09 Ω
			C_G	138 pF
Invest (Fig. 5a)	S_C S_{X1} S_{X2}	NMOS	W / L	10,000 μm / 1.5 μm
			R_{ON}	2.33 Ω
			C_G	17.3 pF
	S_{B1} S_{B2}	PMOS	W / L	40,000 μm / 1.5 μm
			R_{ON}	2.17 Ω
			C_G	69 pF

When harvested energy E_H is sufficient to optimally damp the system, re-investing E_H when vibrations can charge C_{PZ} 5 V (i.e., V_{OC}) generate 91.8 μW while investing alone under the same conditions produce 77.9 μW. This means that re-investing consumes less conduction (R_{ON}) and gate-drive (C_G) power than investing alone does. As a result, as Fig. 8 demonstrates, a battery receives 0.92 μJ every 10 ms when re-investing and 0.78 μJ when investing. Notice that re-investing E_H *and* investing battery energy when E_H is enough to optimally damp vibrations is futile and therefore lossy. Also note an ideal diode-bridge rectifier (where diode voltages are zero) can maximally generate 12.5 μW under the same conditions [8].

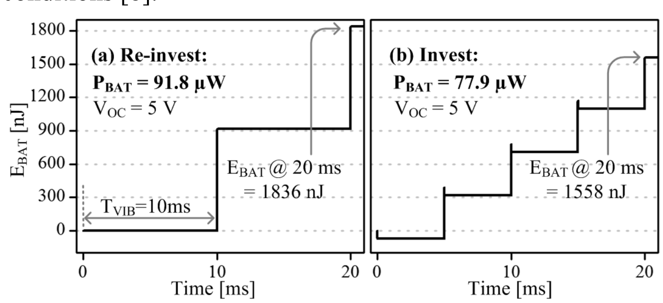

Fig. 8. Charging profiles when (a) re-investing and (b) investing energy.

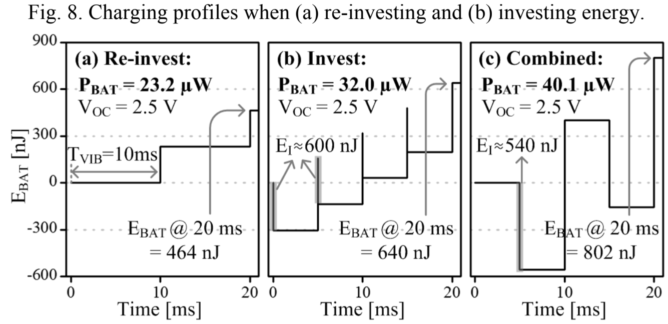

Fig. 9. Charging profiles when (a) re-investing, (b) investing, and (c) both re-investing and investing energy.

When harvested energy is insufficient to optimally damp vibrations, re-investing *and* investing energy when vibrations charge C_{PZ} 2.5 V (i.e., V_{OC}) generates 40.1 μW while re-investing alone produces 23.2 μW and investing alone nets 32.0 μW. This means re-investing alone does not damp the system enough and investing alone dissipates more power than re-investing and investing combined. Therefore, as Fig. 9 shows, a battery receives 401 nJ every 10 ms with a combined strategy and 320 and 232 nJ otherwise. Note an ideal diode-bridge rectifier could draw 3.13 μW at best from the same input [8].

VII. CONCLUSIONS

Re-investing harvested energy E_H generally generates more power than investing battery energy (e.g., 91.8 *versus* 77.9 μW) because transfer losses are lower in the former. If E_H is insufficient to optimally damp the system, however, supplementing E_H with battery energy draws more power than the battery-investment process dissipates when transferring more energy across the system (e.g., 40.1 *versus* 23.2 μW). Plus, supplementing E_H generates more power than replacing E_H (e.g., 40.1 versus 32.0 μW). In other words, while investing energy into harvesters is important because microsystems rarely damp vibrations otherwise, so is adopting a good scheme because it can boost power by another 25%.

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