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Integration of thermoelectrics and photovoltaics as auxiliary power sources in mobile computing applications

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Abstract

The inclusion of renewable technologies as auxiliary power sources in mobile computing platforms can lead to improved performance such as the extension of battery life. This paper presents sustainable power management characteristics and performance enhancement opportunities in mobile computing systems resulting from the integration of thermoelectric generators and photovoltaic units. Thermoelectric generators are employed for scavenging waste heat from processors or other significant components in the computer's chipset while the integration of photovoltaic units is demonstrated for generating power from environmental illumination. A scalable and flexible power architecture is also verified to effectively integrate these renewable energy sources. This paper confirms that battery life extension can be achieved through the appropriate integration of renewable sources such as thermoelectric and photovoltaic devices.

Keywords: Renewable sources; Thermoelectrics; Photovoltaics; Piezoelectrics; Sustainable power management; Battery life extension

1. Introduction

Sustainable power management issues such as the extension of battery life have been receiving increased attention for thin and light mobile computing platforms [1]. Extended battery life has potential impacts on both system performance, as exemplified by a lower maximum clock frequency, and on constraints regarding the attainable thermal envelope. In addition, ergonomic requirements such as a comfortable outer skin temperature, and low acoustic noise from the system fan have also become important considerations. To achieve this extended battery life, the critical development areas that have been identified in the industry include energy efficient cooling, higher density energy sources, fast renewable sources, and enhanced power and thermal management features [2]. Much work has been done on silicon power efficiency techniques, power management features, and new costly cooling technologies. An approach that has not been thoroughly investigated is to model each platform as an isolated island where access to the resources of the "mainland" entails high cost. This dictates the effective use of energy sources in the vicinity of the computer. An example of an energy source in the vicinity of this island is the 50 W (or more) system thermal power dissipated, which, in a size constrained system, has driven elegant cooling technologies [3] such as heat pipes.

A holistic approach is taken in this paper to identify the potential benefits derived from the integration of thermoelectric (TE), photovoltaic (PV) and piezoelectric modules in mobile computing platforms, to potentially extend battery life. The integration of these modules requires appropriate power electronic conversion techniques. To address the additional efficiency issues posed by the implementation of these power conversion approaches, an efficient conversion system was developed to convert low, intermittent voltage levels to an appropriate system dc-bus voltage, using a two level asynchronous Dixon charge pump [4]. Another challenge encountered with the integration of TE devices is the associated increased resistance to heat flow. The proposed solution involves the use of the TE module as a generator in periods of low intensity processor use, and as a cooling device during times of high intensity use [5,6]. This approach essentially allows the excess microprocessor and chipset cooling capabilities, beyond

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those needed by most workloads, to be used to extend the battery life.

This paper reviews previous work in the field and discusses the potential benefits derived from the integration of TE, PV and piezoelectric modules in mobile computing platforms. Sustainable power management issues are also discussed that drive mobile computing design specifications in order to address the fundamental challenges of generating supplemental power from low voltage auxiliary power sources. Analyses and experimental results are included using TE and PV modules, and implementation issues are discussed including the potential benefits derived from the use of state-of-the-art materials and devices in this premium application. Appropriate power architecture designs and control schemes are proposed and demonstrated to effectively and simultaneously employ TE and PV sources to provide supplemental onboard power generation.

2. Sustainable power management

To maximize the potential benefits of integrating renewable sources into mobile computing systems, the desirable system properties must be considered to drive the appropriate design decisions. Thus, it is important to briefly describe and analyze these system parameters.

2.1. Desirable properties of mobile computing

The current design trends in thin and light notebook systems can be summarized as

(i) Longer battery life: new technologies [1] drive energy efficient operation and longer lasting batteries.
(ii) Performance on demand: the performance is expected to scale up to desktop computing capabilities over time.
(iii) Compact design: systems become thinner, smaller, and lighter in order to enable mobility which makes it challenging to cool high power density components.
(iv) Cost: mainstream mobile computing platforms need to pay close attention to costs in order to enable large market penetration.

Clearly, the mainstream mobile computing platforms available in the market lie at the intersection of the above requirements. The “cost” requirement prevents expensive solutions from being deployed to address issues associated with (i)–(iii), though clearly when sufficiently significant gains are possible these solutions will be employed. For example, mobile computing applications have historically been early adopters of advanced battery technology, such as NiMH and Li-ion batteries, which has aided their widespread adoption in more mundane applications (e.g., shavers). Likewise, the adoption of heat pipes in processor cooling in current mobile computing platforms is an example of the adoption of a niche application to address the problem of how to achieve efficient cooling in a very thin platform. It is therefore possible that an option perceived as “expensive” may be adopted as a solution to the problem of extended battery life if the gains in performance are of an adequate magnitude.

2.2. Power and thermal management trends

Effective use of dynamic thermal management is necessary and common in high-performance platforms to reduce the cooling costs. Multiple trigger and response mechanisms that ensure the thermal solution are not designed for statistically insignificant worst case events (i.e., non-realistic scenarios) have been discussed in Ref. [7]. Similar design techniques can also be utilized in battery life limited systems to dynamically trade off performance against power. Some of the trigger mechanisms include feedback from temperature sensors, on-chip activity counters, dynamic profiling analysis, and compile-time insertion of dynamic thermal management instructions. Among the response mechanisms are voltage and frequency scaling, decode throttling, speculation control, and I-cache toggling. For example, the frequency and voltage scaling scheme reported in Ref. [8] yields a 50% power reduction but limits the performance impact to 20% for the duration of the event.

It is expected in the future that adaptive thermal management will allow thermal solutions to be integrated into a closed loop system with silicon triggers, such as temperature sensors, that then respond dynamically to the requirements of a particular application for maximum efficiency and reliability. Fan speed control [9], and Enhanced Intel Speedstep® [10] technologies are examples of this thrust.

2.3. Use of renewables for power management

Scavenging energy from renewable sources in the vicinity of the computing system is conceptually the best method for extending on-board power and thus extending battery life. A significant challenge with small-scale renewable sources is the low efficiency associated with significantly stepping up the low voltage output to allow integration with the system battery. In an extreme case, there may not be a net benefit in on-board power extension after accounting for the power dissipation in the required converter. The problem is compounded when scalability to multiple sources with different characteristics and intermittent properties are considered. To address this challenge, an efficient conversion system was developed to convert low, intermittent voltage levels to an appropriate system dc-bus voltage, using a two level asynchronous Dixon charge pump [4].

Some of the issues related to the development of methods to extract excess heat from the microprocessor with thermoelectric (TE) modules were partly addressed by Solbrekken et al. in Ref. [11]. The modest energy extracted was sufficient to power a small custom-cooling fan to maintain the junction temperature of a 25 W component under 85 °C. Energy storage was not viable due to the power electronics limitations and required auxiliary kick-start circuitry. In their work, a constant heat source was used in the demonstration experiments in lieu of an actual, dynamic microprocessor. The thermal efficiency cost of the integrated TE module under the heat sink was estimated as a 10–15 W reduction in cooling capacity. The lower cooling capacity can be converted to performance reduction for components such as microprocessors where power dissipation varies linearly with operating clock frequency. Their solution also utilized sizeable heat sinks and a fan in the vicinity of the microprocessor, which renders it inappropriate for direct application in compact mobile systems.

A second potential energy source with potentials ranging from the mWatts to Watts range is the use of photovoltaic (PV) modules. Emerging solar cell technologies with cell thicknesses between sub-micron and a few micrometers have been reported, enabling the reduction of PV module costs [12]. Proposals include concepts such as external foldable thin film modules that can be spread flat next to the notebook, and connected to the dc power inlet [13,14]. This usage model requires carrying an additional component, and reserving space next to the notebook to set it up. The alternative is to integrate the PV module on the dead space at the backside of the notebook lid. A small solar powered personal digital assistant (PDA) was demonstrated [15] to provide sufficient power to charge the batteries using indoor conditions. In this system, only 22 mA were available due to size limitations. Although sufficient for PDA operation, this PV solution scaled up to the area on the backside of a notebook is insufficient to power a thin and light mobile computing system. The option of including a PV layer in the front side of the display, which has the added benefit of increasing the contrast levels of displays, has also been suggested in the past [16].

A third option in the integration of renewable power into portable electronics would be the use of piezoelectric generators, for example harvesting energy from vibrations. An aspect that contrasts the integration of this mode of scavenging parasitic power is that while in operation, most mobile computing devices prefer not to encounter (or produce) a high amount of vibration. Piezoelectrics integrated into computer keyboards is also being investigated to generate charge upon key striking [17]. However, this can alter the tactile response of the user, and is thus not as of yet a transparent approach without potential negative impact to the user. For this reason, the authors propose that integration of piezoelectric generation in portable electronics using vibrational energy will find itself focused on the intervals where the device is transported in a low power state, between episodes of active use. Further, high-end portable electronics, such as the mobile computing applications, which this paper focuses on, are usually handled with care and highly protected from sustained violent motion. As a consequence, sustainable power generation through the use of piezoelectric devices using vibration should be more adequate for applications such as cell phones, PDAs and other small portable electronic devices, and thus will not be further considered in this paper.

2.4. Sustainable power management approach

The approach taken in this work focuses on the goal of efficiently enabling energy harvesting from renewable sources to be made available to the mobile computing system as a means for extending battery life. This approach also advances recent industry initiatives to design computer platforms with environmentally friendly characteristics such as energy star [18]. Example characteristics to ensure mobile platforms with sustainable power management are superior to the existing systems are identified below:

(i) Battery life assumptions: longevity should be improved by providing net charge directly to the system battery instead of powering up specific sub-systems (as opposed to the implementation in Ref. [11]). The generated power must be higher than the power dissipated in the power electronics interfacing with the renewable sources for net battery life benefit. Renewable sources like PV components should be enabled to scavenge energy even when the system is off. They should otherwise supplement externally supplied ac power or dc power from the battery even when the battery is fully charged. This is a highly desirable attribute for a truly green implementation.

(ii) Performance assumptions: it is not acceptable to degrade system performance as a result of integrating renewable sources. For example, TE components used to scavenge thermal energy should operate in hybrid mode, as discussed in Refs. [5,6], in order to offset negative performance impacts from reduced cooling capacity, and even improve performance when required by the system tasks.

(iii) Size, cost, and scalability assumptions: the added renewable components and associated power electronics should represent common technologies to allow lowest costs. They should also be scalable with system size. The power electronics should be compact, and easy to integrate into an LSI chip. Magnetic components should therefore be minimized or avoided.

3. Experimental

TE and PV devices are the two promising renewable energy sources investigated in this experimental validation for enhanced power management in mobile computing systems. The TE and PV modules employed in this study were readily available off-the-shelf modules purchased from TE Technology, Inc. [19] and Radio Shack [20], respectively. Module efficiency measurements were conducted with a data-logging device built using a Vernier LabQuest module coupled with voltage and current measurement probes [21] using a precision decade box as a resistive load.

Measurements of PV module performance were taken using a scalable panel built from 5 series, ×3 parallel modules of 0.8 in. × 1.6 in. dimensions (1.3 in^2 or 8.5 cm^2), resulting in a total area of 19.2 in^2 (124 cm^2). Measurements of incident radiation were taken using a first class silicon primary pyranometer [22] purchased from Apogee Instruments, Inc. [23]. First-order analysis was conducted through simple application of the cosine law, reported indoor [24] and outdoor [25] irradiance data from the literature, and the range of efficiencies for an integrated PV component. Notebook lid tilt effects were taken into account through weighted average models.

Measurements of thermoelectric module performance were conducted using a test system consisting of a heated aluminum block as a heat source and an aluminum block at room tem-

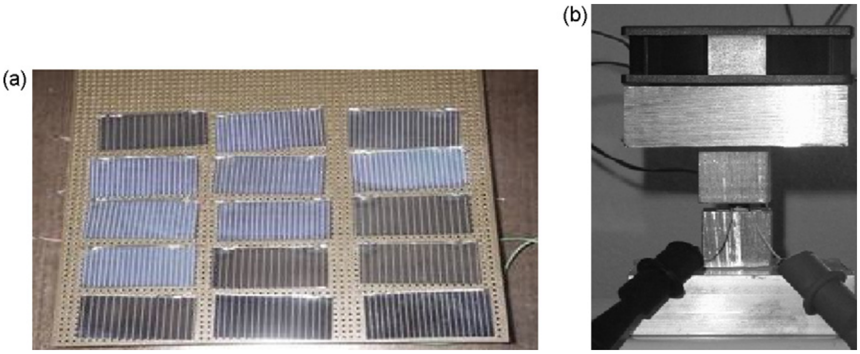

Fig. 1. (a) PV module used for device characterization and (b) TE micro-module characterization setup.

perature as the heat sink, while using procedures similar to those delineated in Ref. [26]. Both the interfaces between the aluminum blocks and the thermoelectric modules were instrumented with thin thermocouples used to measure temperature and temperature distributions. Photographs of the two experimental devices are shown in Fig. 1. As discussed, for system power electronic conversion validation, a double Dickson charge pump was constructed using 1N5817 Schottky diodes and discrete capacitors for both the 1st and 2nd stage [4].

4. Results and discussion

To ensure that design parameters were based on the characteristics of readily available and typical TE and PV modules, off-the-shelf devices from commercial sources were purchased and their performance was experimentally determined. The results extracted from these measurements were then used to design the power extraction approaches.

4.1. Thermoelectrics (TE)

The heat source of highest interest for integration of thermoelectric generators is the system's CPU [11]. However, integration of this heat source is non-trivial. While it is desired that as much power as possible is extracted from the system, it is also crucial that the temperatures that the CPU experiences are not allowed to exceed manufacturer specifications. For this purpose, a shunt-attach hybrid thermoelectric conversion concept (HTC) was developed [5,6]. This design is based on semi-realistic workload models such as the MMO5 Office Productivity benchmark [27], which is frequently used for platform average power calculations. In such a configuration, the TE module is integrated into the heat-pipe attach on the CPU and Chipset to scavenge heat energy and operates on the principle that:

- The majority of the time, low demands are placed on the CPU, and power is scavenged from the waste heat, converting the margin in cooling into electrical energy.
- During those short periods of time when extra performance is needed, determined either when high temperatures are detected at the CPU heat-pipe attach, or using more sophisticated approaches directly tied into the processor load, current is forced through the TE module causing it to act as a cooler, consuming some power.

This extends the available thermal design power (TDP) envelope for heavy workloads beyond what was possible without using TEs. The TDP envelope for a thermally limited platform can be used as a proxy for performance [6]. The waste heat generated by other system components, such as the graphics chipset, can also be utilized. Due to the constant performance requirements placed on such subsystems, and a significant margin included in its cooling capabilities, the TE module in this case needs only to operate in generation mode.

The commercially available TE module was characterized using the setup in Fig. 1(b), and the measured device Seebeck coefficient (mV °C^{-1}) versus ΔT, and power output versus ΔT, are given in Fig. 2. Both voltage and power output from the Micro-TE module show an essentially linear dependence on the temperature differential applied over the range of temperatures employed, and therefore, power output is seen to vary with the square of the temperature difference.

Further, the results indicate that the use of an off-the-shelf TE device at room temperature yields an average measured module Seebeck coefficient of 0.33 mV °C^{-1}. The use of state-of-the-

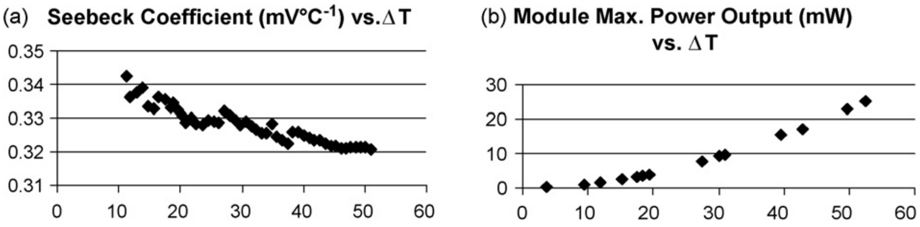

Fig. 2. (a) Measured device Seebeck coefficient (mV °C^{-1}) vs. ΔT and (b) maximum power output vs. ΔT for the TE module employed.

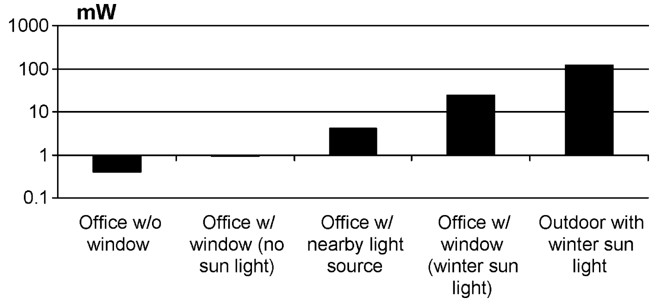

Fig. 3. PV generated power vs. environmental condition scenarios, experimentally measured in OR, USA.

art TE materials and devices could significantly improve system performance. For example, novel materials with high ZT figures of merit may be considered, which implies efficient usage of heat by achieving very low thermal conductivities while retaining acceptable Seebeck coefficients and material electric conductivity. An alternative would be to employ high Seebeck coefficient materials, even if the overall use of thermal power is not as efficient due to losses arising from higher thermal conductivities. Examination of the heat system described, where heat dissipation is the primary function rather than power generation, argues that the preferred option would be the use of a high Seebeck coefficient material (even with the compromise of a lower ZT figure of merit). This suggests that for cooling limited applications, a systematic investigation of the technical literature should be carried out to determine the quality of the match between the application materials. A parameter that may guide the selection of materials for applications such as that described here is the thermoelectric compatibility parameter [28] which helps move beyond the raw efficiency metric of a ZT figure of merit to a more sophisticated system-based compatibility figure of merit.

4.2. Photovoltaics (PV)

Integration of PVs has been targeted for the backside of a notebook lid, and adjusted for two typical device lid sizes. The test panel was fully characterized in different environments during winter in OR, USA. As expected, the generated power varied super-linearly with light intensity, but the light intensity itself varied logarithmically across environmental conditions. Results from varying illumination conditions dependent on environmental situations are shown in Fig. 3. As summarized in Table 1, the average power generation from an integrated thin film PV module varied with system size.

The generated power can vary between sub-mW to mWs in office environments with artificial lighting, and can range from tens of mWs to hundreds of mWs with exposure to natural light, illustrating that off-the-shelf PV integration can improve battery life by up to 5%. A brief characterization of the actual PV device used indicates its overall efficiency (electrical power generated/incident solar energy) is 7.1% with a fill factor of 42.8%. In comparison, if a very high efficiency multijunction device was employed, such as those manufactured primarily for the space program [29] with a reported efficiency close to 40%, the power produced would be sufficient to extend the battery lifetime by approximately 25%. Such a pronounced gain in performance may make the inclusion of such high-end PV modules in existing premium applications such as high-performance portable computing devices desirable.

Table 2
Current, voltage, and power range for TE and PV integration

Design range	I (mA)	V (V)	P (mW)
TE	0–50	0–0.5	0–25
PV	1–100	0.5–5	0.5–500

4.3. Integration issues concerning TEs and PVs

The off-the-shelf TE and PV current, voltage and power parameters for this experimental work are summarized in Table 2. Clearly, for integration of these generator modules into a mobile computing platform, voltage conversion/boosting to appropriate bus levels will be required. To maximize the efficiency of the boost converter, the voltage settings at the internal bus need to be optimized for best overall input to output power efficiency.

Further, it should be noted that the low voltage threshold of the PV module is similar to the high voltage threshold of the TE module. Therefore, it is apparent that if both modules are to be employed simultaneously, the choice of voltage levels in a converter is crucial, with the lower voltages provided by the TE module boosted to the levels output by the PV module as an intermediate stage. From the viewpoint of maximum efficiency, an optimal intermediate voltage is likely to be such that the first stage and second stage boost multipliers are simultaneously minimized, and hence are roughly equal.

Based on operating conditions, it is possible that the power supplied by the auxiliary power source (e.g. the TE generator) may at times be less than that consumed by the converter power electronics. Therefore, to achieve the goal of net power generation, system ON/OFF thresholds must be included for the low end of the power range, so that at least part of the voltage boost converter is deactivated when the converter power consumption is expected to be higher than the generated power. Since voltage, current, and power scale together for TE and PV, just one of these parameters can be utilized for the ON/OFF thresholds. Suitable choices for control parameters include the voltage generated by

Table 1
Average PV power estimation based on predominantly indoor and outdoor usage models and different form factors

Notebook type (lid surface area)	Portable, (10 in. × 12 in.)		Ultra-portable, (6 in. × 8 in.)	
Power (mW) generation predominantly indoors	Minimum 127	Maximum 510	Minimum 51	Maximum 204
Power (mW) generation predominantly outdoors	Minimum 415	Maximum 1662	Minimum 166	Maximum 665

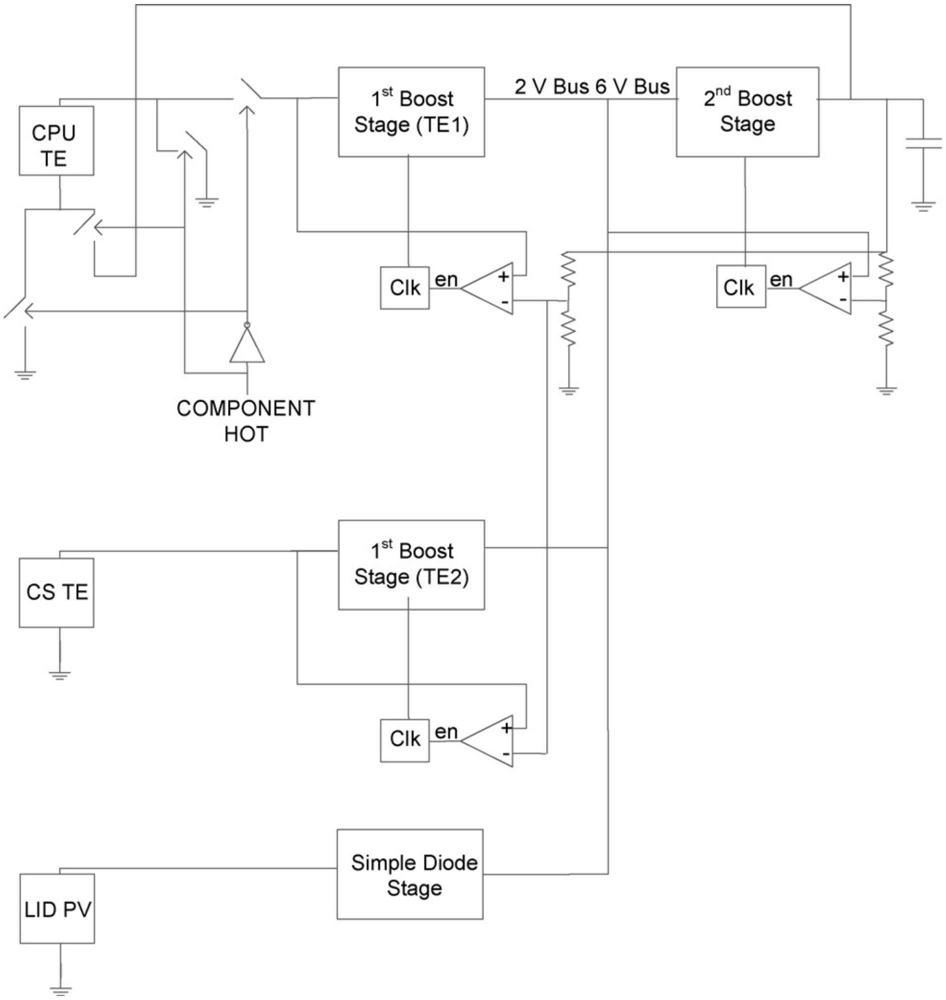

Fig. 4. Proposed power architecture for integration of low voltage (TE) and high voltage (PV) auxiliary power sources into mobile computing system bus.

the TE module for the first stage of the converter, and available current to the device in the second stage.

A final issue to consider in the design of the auxiliary power system is the ability to enable the TE device to operate in hybrid thermoelectric conversion (HTC) mode (either generating electrical energy or operating as a cooler) as described in Section 4.1 above. Therefore, a switch is required that upon sensing elevated temperatures at the CPU, isolates the CPU TE module from the converter and operates the TE module as a cooler. For optimized implementations, a "smart switch" could be employed to control the power used for CPU cooling that would drive the junction temperature to just below the design temperature to enable minimal power consumption during high processor demand events.

The proposed power architecture for the integration of low voltage (TE) and high voltage (PV) auxiliary power sources into a mobile computing system bus is given in Fig. 4. The voltage boost takes place in two separate stages, where the lowest voltage module, e.g. the TE converter, is boosted to a level similar to that encountered with the expected output of the PV module, and then the combined power from these two sources is boosted to a higher bus compatible voltage. This has the advantage of minimizing the power electronic components, leading to a more robust and less expensive system. Should it be desired, thermoelectric converters scavenging power from other chipset components known to operate significantly above room temperature (such as the graphics accelerator set) can be added to the system. This chipset thermoelectric module is shown in Fig. 4 as the "CS TE" module.

4.4. Simulation and experimental proof of concept results

In order to validate the overall system proposed in Fig. 4, a boost converter based on two tandem Dixon charge pumps [4] was designed as shown in Fig. 5. The two-stage Dixon charge pumps are designed to interface between the low voltage TE (1st stage) and higher voltage PV (2nd stage) modules and the mobile computing system bus voltage (the 6 V bus in Fig. 5). Simulation results are shown in Table 3 and presented graphically in Fig. 6, indicating that lower voltages and smaller capacitors utilized in the charge pump result in higher efficiencies. The significant power scaling with supply voltage can be attributed to smaller voltage swings induced in the charge pump switching capacitors

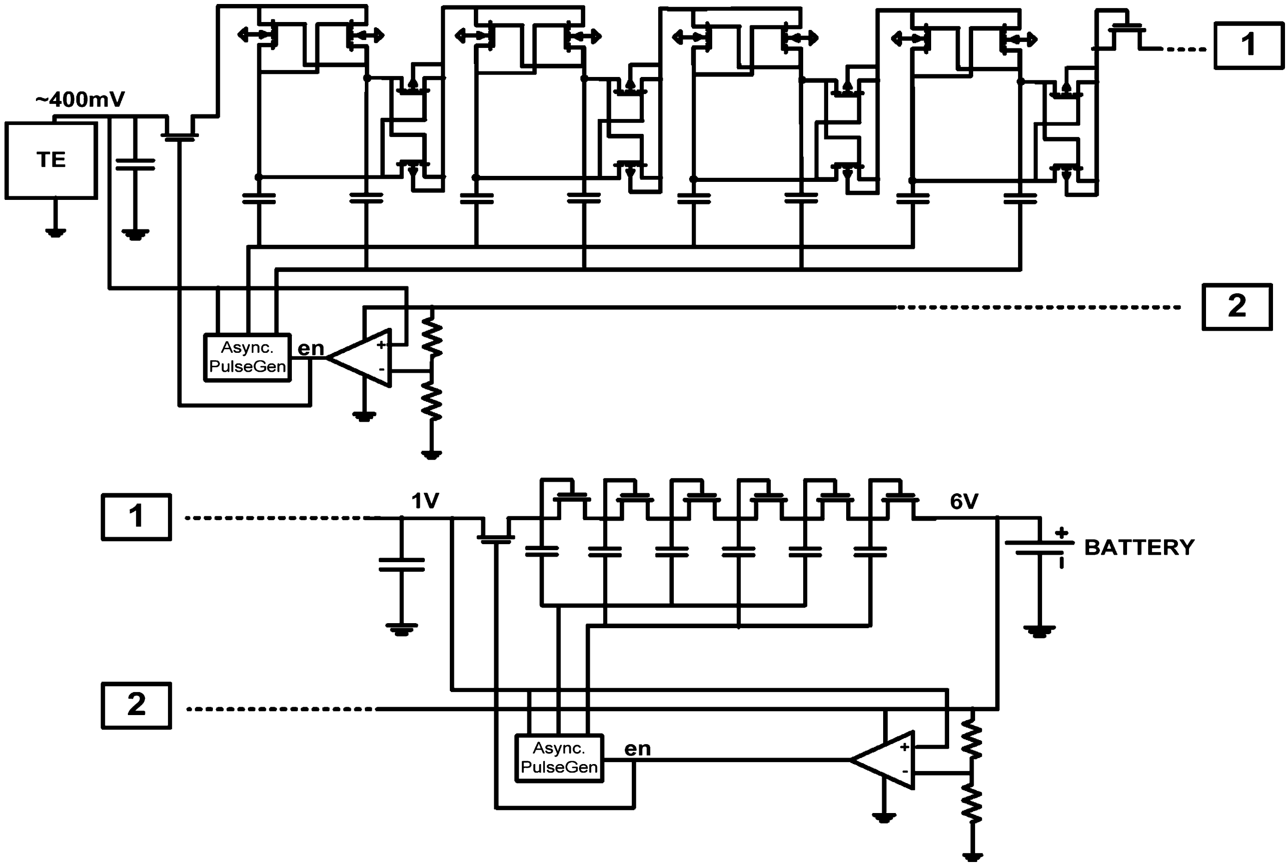

Fig. 5. High efficiency two-stage Dixon charge pump voltage boost converter.

Table 3
Design parameter selection for complete generation system

1st stage supply voltage (V)	2nd stage supply voltage (V)	Generation surplus (mW)	Input-to-output efficiency (%)
1.5	3.5	270	57%
2	4	30	52
2	5.5	−240	42
2	5.5	−410	39
5.5	5.5	−2750	27

Table 4
Measured TE generation efficiency when interfaced with mobile computing bus through two-stage Dixon charge pump converter

Supply (V)	1
TE source power (mW)	4.5
Consumed by converter (mW)	2.5
Generation surplus (mW)	2.0
Input–output efficiency (%)	45

at low voltages. Thus, lowering the switching voltage reduces the power losses in the switches.

The simulation design and results above were then used to experimentally verify the two-stage Dixon charge pump converter, constructed using discrete off-the-shelf hardware components. The two-stage Dixon charge pump was tested using the TE module as the renewable power source, and the experimental results are given in Table 4. The overall input/output efficiency of the system was 45%, and the hardware implementation showed excess power at the output that could be used to

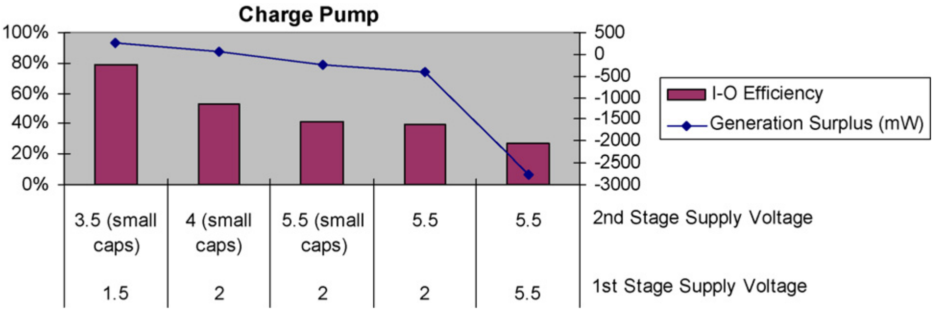

Fig. 6. Graphical representation of design parameters determined for voltage boost converter operation.

supplement battery power. Note that the overall converter and TE interface efficiency could be improved through optimizing the charge pump converter design using monolithic integrated circuit (IC) implementation.

5. Conclusions

Future power management breakthroughs in mobile computing systems will include the widespread use of renewables to scavenge energy from the surrounding environment. In this paper, sustainable power management issues were discussed that drive mobile computing design specifications in order to address the fundamental challenges of generating supplemental power from integrated sources such as thermoelectrics (TEs) and photovoltaics (PVs). Appropriate designs and control schemes were proposed and demonstrated to effectively and simultaneously employ TE and PV sources to provide auxiliary onboard power generation. This power can be used for performance enhancements in mobile computing systems, such as for extended battery life. Opportunities for significant gains were also presented from the use of high-performance, premium generation modules in high-end mobile computing devices.

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