Energy and Operational Benefits of Thermoelectric Chillers in Semiconductor Manufacturing

Nicholas Collins, Energy & Resource Solutions (ERS)

ABSTRACT

Semiconductor manufacturing is a high-tech industry that relies heavily on automated tools in the fabrication process. With technologies down to 0.18micron and even smaller line widths, semiconductor products are extremely sensitive to produce, and many manufacturing tools require dedicated process cooling that is typically provided in the form of a dedicated conventional vapor compressor chiller. In 2010 National Semiconductor's Portland, Maine facility retrofitted forty-nine existing vapor compressor chillers to thermoelectric chillers. This paper details the retrofit project and the significant energy savings that were realized.

National Semiconductor Maine (NSME) is a Class 1 200mm wafer fab with 80,000 square feet of manufacturing space. In an effort to reduce the considerable energy associated with wafer fabrication, NSME installed forty-nine Solid State Cooling ThermoRack 1200 W thermoelectric chillers. Thermoelectric chillers (TECs) utilize the Peltier effect in order to transfer heat through electron flow. The TECs reduce the energy associated with process cooling and significantly reduce the amount of heat rejected into the fabrication space, thereby reducing the load on the space cooling systems. On average, direct energy use was reduced by 1.873 kW per retrofitted chiller with total (direct and indirect) annual electric savings of 827,976 kWh.

The project was partially funded through Efficiency Maine's custom incentive program, which provides cash incentives for projects that demonstrate electrical energy savings meeting prescribed simple payback and benefit-cost ratios. Due to the success of the project in terms of energy savings and process stability, National plans to install an additional fifty thermoelectric chillers in 2011.

A review of the literature on solid state or thermoelectric cooling reveals little in the way of case studies or commercialized products and focuses instead on the theoretical and experimental aspects of the technology. This paper will report on the details of the installed system, and pre- and post-metering results.

The Application

National's flagship manufacturing facility is located in South Portland, Maine where 200 mm wafers are fabricated to the specifications of their customers. The manufacturing floor, referred to as the "ballroom," is an 80,000 square foot Class 1 clean room with over 100 automated tools used in the manufacturing process. Beneath the ballroom is the return air plenum (RAP), a space as large as the ballroom above where supporting and ancillary equipment is housed, such as dedicated tool chillers, de-ionized (DI) water systems, and heat recovery equipment.

In 2009 NSME and Efficiency Maine (EMaine) met to discuss a conceptual project that involved the replacement of existing dedicated vapor compressor tool chillers with thermoelectric chillers. An opportunity to significantly reduce the electrical energy consumption associated with the chillers was evident upon initial meetings. The project would also increase reliability and process stability and reduce scheduled maintenance time associated with the chillers. Following the initial meetings, EMaine and NSME began the process of analyzing the proposed project for electrical savings and site-specific economic impact in earnest.

The project team consisted of the following companies:

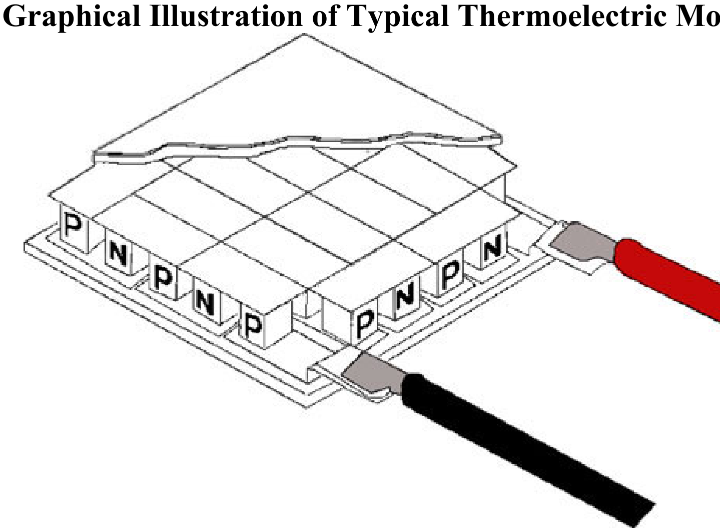
- National Semiconductor, Maine: Project manager, owner and operator
- ERS: Efficiency Maine Delivery Team, system analysis
- Solid State Cooling Systems: Designer, manufacturer, and installer of thermoelectric chillers

A Brief Review of Thermoelectric Cooling Technology

A thermoelectric module is a solid state heat pump in which the medium for heat transfer is the electron. In a compressor-based chiller or heat pump, refrigerant is the medium for heat transfer. In general terms, a thermoelectric module is a closed circuit made of two dissimilar metals. When DC current is applied to the module, heat is absorbed at one dissimilar metal junction and discharged at another (Dieckmann, Cooperman, & Brodrick 2011). Therefore thermal energy can be moved from the cold side to the hot side, where the heat can then be removed through a heat sink and rejected to any number of mediums. French physicist Jean Peltier discovered this effect in 1834 and it is often referred to as the Peltier effect. It is closely related to the reverse effect, known as the Seebeck effect, which is the basis for thermocouples.

Modern thermoelectric (TE) modules used for cooling typically consist of semiconductor "nuggets" of bismuth telluride sandwiched between copper plates or junctions with ceramic plates on the exterior. Figure 1 below illustrates a typical TE module.

Figure 1. Graphical Illustration of Typical Thermoelectric Module



Source: Solid State Cooling Systems

Due to limitations in available semiconductor materials and the current state of the technology, thermoelectric chillers are best suited for jobs with small to medium cooling loads (Dieckmann, Cooperman, & Brodrick 2011). The physics describing the current limitations of thermoelectric chillers is well beyond the scope of this paper, however, thermolectric chillers for process cooling are generally offered in the 100-6000 watt range. A comparison of thermoelectric chillers to vapor compressor chillers is illustrated in Table 1 below.

Table 1. Thermoelectric Chillers vs. Refrigerant Based Chillers

Property	Thermoelectric Chiller	Refrigerant Based Chiller
Cooling capacity	Low to moderate	Moderate to high
Cooling engine	Thermoelectric device	Gas compressor
Power	Variable output DC power supply	Electric motor
Control method	Infinitely variable	On/Off
Refrigerant	None	HFC/HCFC

Source: Solid State Cooling Systems

Installation and Performance

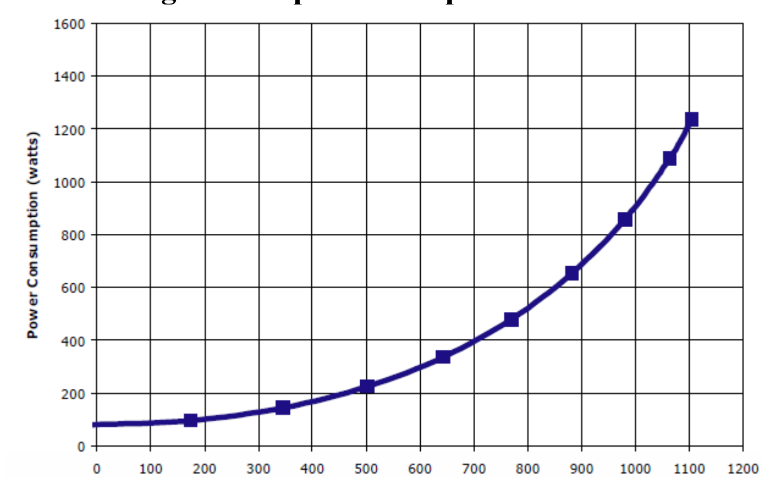
NSME had plans to install fifty TECs to replace existing Edwards TCU 40/80 vapor compressor chillers. Each of these chillers is dedicated to one automated tool and handles the cooling load from that tool alone. The chillers all serve tools that perform the same process, therefore each chiller experiences the same thermal load. Manufacturing at NSME runs twenty-four hours a day throughout the year, and great emphasis is placed on keeping tools up and running at all times. This schedule also contributes to a very consistent thermal load.

Ultimately forty-nine chillers were replaced with TECs, and this paper will focus on the forty-one Edwards TCU 40/80 chillers that were replaced with Solid State Cooling Systems ThermoRack 1200 W TECs.

Determining Performance

Figure 3 below represents the typical performance of a ThermoRack 1200.

Figure 3. Input vs. Output ThermoRack 1200



Cooling output (watts)
Source: Solid State Cooling Systems

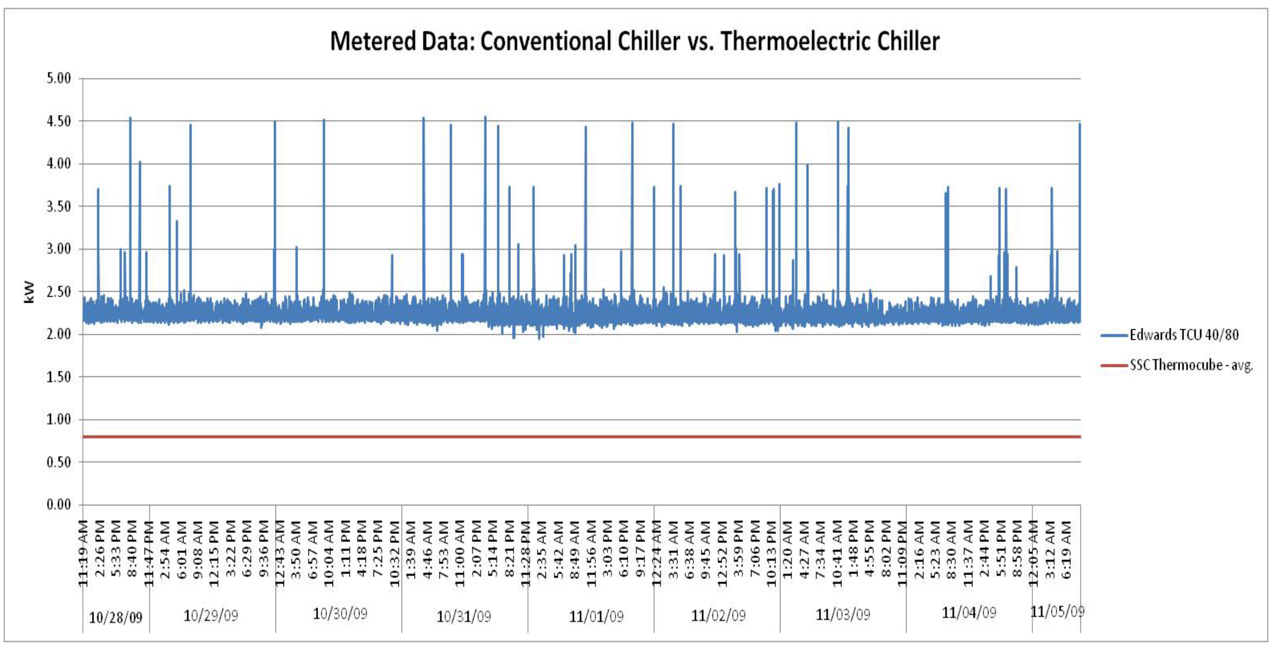
EMaine is tasked with administering energy efficiency and alternate energy programs in the State of Maine. One of EMaine's efforts is the Business Program, which provides cash incentives and technical assistance to qualifying energy efficiency measures.

National Semiconductor approached EMaine about participating in the custom incentive program for the retrofit of the existing chillers. Initially NSME had received estimations of savings calculated from several TEC vendors and these were passed on to EMaine as evidence of the savings and justification for the requested incentive.

The calculations represented significant savings, and the technology was new to both NSME and EMaine, therefore in-situ metering of both the existing and the proposed chiller was necessary to quantify the savings. Prior to purchase, the vendor installed one of the proposed units in order to verify performance and capability.

NSME installed metering equipment on the Solid State Cooling (SSC) TEC unit and EMaine installed power loggers on the existing vapor compression chiller. Figure 2 below represents the results of the metering over a 7-day period. It should be noted that the TEC unit was operating with an incoming fluid temperature of 70 C. This was done to ensure the capability of the unit in a "worst case" scenario, but did not represent anticipated operating conditions.

Figure 2. Metering Results



Indirect Energy Savings

In addition to direct electrical energy savings associated with the chillers, there are indirect savings on the plant cooling system. In NSME's case, the heat rejected by the chillers is transferred into a plant-wide process water-cooling loop, which is sent to water-cooled chillers. Although both the conventional chiller and thermoelectric chiller are rejecting the same amount of process heat to the cooling loop, the thermoelectric chiller uses less energy to accomplish the task. In this way, the heat generated by the unit itself and rejected into the RAP is less than the conventional chiller. Less heat rejected to the return air plenum space reduces the overall load on the cooling system and subsequently reduces the energy use associated with maintaining specific temperature and humidity set points in the fabrication space and RAP. Although not metered directly, approximate savings associated with the cooling system can be calculated from metered power data on the chillers and an approximate overall efficiency of the plant cooling system.

Post Installation Inspection

Following the installation of the units, EMaine performed a site inspection along with staff from National Semiconductor. NSME reported excellent performance and temperature stability and was very pleased with the compact design and space saved.

Post install metering revealed that the TEC units on average were consuming 327 watts, 1.873 kW less than the vapor compression chillers.

Summary of Savings

Table 2 below illustrates the direct savings associated with retrofit of forty-one Edwards TCU 40/80 compressor-driven chillers with forty-one Solid State Cooling Systems ThermoRack 1200 thermoelectric chillers and Table 3 illustrates the indirect savings associated with the reduced load on the plant cooling system. Plant cooling system efficiency is estimated at 0.8 kW/ton based on historical performance and observations made by NSME facilities staff.

Table 2. Direct Energy Savings

	Unit	Quantity	Average kW	Annual Run Hours	Annual Direct Electric Use - kWh
Existing	Edwards TCU 40/80	41	2.2	8660	781,132
Proposed	SSC ThermoRack 1200	41	0.3	8660	106,518
				Annual kWh Savings	**674,614**

Table 3. Indirect Energy Savings

	Unit	Quantity	BTU per Unit	Annual Run Hours	Annual Indirect Electric Use - kWh (assumes 0.8 kW/ton cooling efficiency)
Existing	Edwards TCU 40/80	41	7502	8660	177,577
Proposed	SSC ThermoRack 1200	41	1023	8660	24,215
				Annual kWh Savings	**153,362**
				Total Annual kWh Savings	**827,976**

Partnering and Economics

When NSME approached EMaine, they made it clear that the corporate entity required a specific payback in order to approve any capital improvement projects. Based on the project cost and estimated savings, the proposed retrofit of conventional chillers with thermoelectric chillers did not meet the required payback period. As an incentive program, EMaine was able to lend financial assistance if the savings and project costs met the simple payback and benefit/cost ratio that the custom incentive program requires.

After reviewing the metered data and performing an analysis to determine total savings associated with the project, EMaine was able to offer NSME $300,000 to help fund the project. In turn, the $300,000 incentive brought the payback period down to what was mandated by NSME's capital expenditure requirements.

Conclusions

In the correct application, thermoelectric chillers can yield substantial savings over compressor-based chillers. There are also numerous other advantages especially important to the semiconductor manufacturing process such as reduced equipment footprint, precise temperature control, and a significant reduction in required maintenance.

The implementation of thermoelectric chillers needs to be carefully considered. Cooling capacity, load cycling, and equipment communication protocols are all unique to each application and therefore close coordination and communication with the vendor or manufacturer is necessary; the technology is not "plug and play."

There are significant first costs associated with these units as well. As noted, without the incentive from EMaine, National Semiconductor would not have been able to proceed with the project due to the payback period. However, the potential savings do make the technology an attractive opportunity for partnering with energy efficiency incentive programs such as Efficiency Maine.

References

Dieckmann, J., Cooperman, A., & Brodrick, J. 2011. "Solid-State Cooling, Part I." *ASHRAE Journal*, 53 (3): 82-84.