Institution:
University of Cambridge

Unit of Assessment:
UoA15

Title of case study:
Enecsys

1. Summary of the impact (indicative maximum 100 words)

Research by the University of Cambridge Department of Engineering (DoEng) on high-reliability micro-inverters for use in solar power systems was commercialised by DoEng spin-out company Enecsys Limited. Since 2008, Enecsys has attracted GBP34M in private investment, increased its number of employees from 7 to 75 people across three offices in Europe, North America and Asia-Pacific, and shipped more than 150,000 micro-inverter units. Its revenue in financial year 2012/13 was USD11.7M. Solar power installers have confirmed that Enecsys' products, in comparison with traditional string inverters, are: easier, cheaper and safer to install; more reliable; and able to extract more energy from an array of solar panels. Enecsys products are also changing the market for solar power with simple plug-in solutions that home owners buy from retailers and install themselves.

2. Underpinning research (indicative maximum 500 words)

Gehan Amaratunga became a Professor in the DoEng in 1998 and led the Power Electronics Group. Amaratunga set his strategic research aim to be power electronics for energy efficiency and renewable energy sources, particularly solar photovoltaic (PV) power. He reviewed the state-of-the-art of solar PV technologies in 1998 to refine his research aim and to inform the creation of a new teaching module. During this analysis, Amaratunga realised that the deployment of solar PV systems for integration with mains voltage circuits and the grid was being hampered by the cost and reliability of "string" inverters. A typical installation would use one or two of these inverters to convert the 200-800V DC output from a string of PV panels in series creating a complex, expensive and hazardous single point of failure. Micro-inverters had been proposed by others, but the high component count created cost and reliability problems. Amaratunga's systems-level analysis and detailed knowledge of power control devices led to his conclusion that micro-inverters of sufficiently low cost and reliability could be deployed on each panel to great advantage with a control architecture that eliminated a single point of failure and allowed optimisation of energy transfer from each panel. Amaratunga published his broad vision (Ref 1).

Amaratunga secured funding from Semelab, a UK-based semiconductor firm for an ambitious research project (1999-2003) to investigate the ideal option for a solar PV micro-inverter: a monolithic integrated circuit using Silicon On Insulator (SOI) technology for both the management and control functions of the micro-inverter. The research used simulation to explore the design of such an integrated circuit, Semefab (a subsidiary of Semelab) made experimental circuits for the team, and these circuits were tested at the DoEng. The project was successful. It showed that multi-voltage-level power electronic circuits working at different switching frequencies could be integrated on the same substrate. Specifically, it showed that low-voltage (~70V rated) first stage Metal Oxide Semiconductor Field Effect Transistor switches and high-voltage (~300V rated) second stage LIGBT (Lateral Isolated Gate Bipolar Transistor) switch bridge inverter circuits could be integrated on a single chip and applied to micro-inverters for solar PV.

In 2000-05, Amaratunga undertook another research project in parallel with the first. This project focussed on control aspects of solar PV systems, which were now viewed as key. It was funded by the Cambridge Commonwealth Trust and an EC FW5 project called USHER "Urban Integrated Solar Hydrogen Economy Realisation". This research was focused on the system-level performance of solar installations. The first challenge was to maximise the energy harvest of an array of panels by minimising the impact of individual panel output variations caused by factors such as shading. The second challenge was to achieve electronic control and efficient transfer of small amounts of power to the grid, for instance, when a micro-inverter was handling only 25W from a single 250W-rated panel running at 10% of its capacity (in comparison, it was relatively

easy to design a traditional string inverter for a typical array of 20 similarly rated panels, which would be handling 500W at 10% capacity).

The research was not published because Amaratunga and his research team founded Enecsys Limited in July 2003 to exploit their results and they needed to apply for patents. The first patent (Ref 2 with a priority date of 6 May 2003) describes the fundamental architecture of a micro-inverter together with its control strategy. It also includes the invention of a single chip monolithic integrated circuit implementation of the micro-inverter. It embodies the results of the research carried out by Amaratunga and his team during the period 1999–2003 and underpinned Enecsys. Amaratunga led further research in the DoEng with funding from Enecsys between 2003 and 2006.

The research at the DoEng combined theoretical studies, analysis and simulation with practical experiments. Solar PV arrays were built in the DoEng and used extensively for trials. The focus shifted substantially from the single chip concept to address the complex issues of the dynamic stability of grid-connected solar PV systems and their control. In particular stable and novel methods for Maximum Power Point Tracking emanated from the research (Refs 3 and 4 with these results protected in US patent 8405367). A number of new strategies and methods for improving the dynamic stability of micro-inverters also resulted from the research. This systems-level analysis then moved forward to address the long-term performance of solar PV micro-inverter systems (Ref 5). Another major outcome of the research was the elimination of the need for electrolytic capacitors, which are unreliable and limit the period over which failure free operation can be obtained. This was achieved with a novel architecture which drastically reduced the amount of capacitance required for energy ballasting in a single phase inverter (where the grid power periodically transitions through a zero point, while the solar panel keeps generating power). This enabled the use of long-life time polypropelene capacitors, which are not available at high capacitance, and solution of the reliability limitations (Ref 6 with the results protected in US patent 7626834).

3. References to the research (indicative maximum of six references)

1. Amaratunga, G.A.J. and Lorenz, L. Electronic devices for power switching and power integrated circuits: the enabling technology for clean energy. Invited paper. World Microtechnologies Congress, Expo 2000, Hannover, Germany, September 2000, 1, 407 (VDE Verlag, 2000), ISBN 3800725797
2. *Power Supply Circuits. Patent. Inventors: Mumtaz, A., Chisenga, L. and Amaratunga, G.A.J. Priority date: 6 May 2003. PCT publication date: 18 November 2004. Patent number: US8067855.
3. Rodriguez, C. and Amaratunga, G.A.J. (2006) Lyapunov's stability and operational margin of grid-connected photovoltaic modules. Proceedings of the IASTED International Conference on Energy and Power Systems, Chiang Mai, Thailand, 2006. pp. 178-183, ISBN 0-88986-586-8
4. Rodriguez, C. and Amaratunga, G.A.J. (2007) Analytic solution to the photovoltaic maximum power point problem. IEEE T Circuits and Systems-I, 54. pp. 2054-2060, DOI: 10.1109/TCSI.2007.902537. ISSN 1549-8328
5. *Rodriguez, C. and Amaratunga, G.A.J. (2006) Dynamic maximum power injection control of AC photovoltaic modules using current-mode control. IEE P-Elect Pow Appl, 153. pp. 83-87, DOI: 10.1049/ip-epa:20050246. ISSN 1350-2352
6. *Rodriguez, C. and Amaratunga, G.A.J. (2008) Long-lifetime power inverter for photovoltaic AC modules. IEEE T Ind Electron, 55. pp. 2593-2601, DOI: 10.1109/TIE.2008.922401. ISSN 0278-0046.

*Outputs that best represent the quality of the research.

4. Details of the impact (indicative maximum 750 words)

In 2003, Enecsys Limited was founded by Amaratunga (as Chairman), his research team and an MBA student from the Judge Business School, who led the development of the financial business plan. This followed their success in winning the Cambridge Business Plan Competition earlier in the same year (with the name “Cambridge Solar Electronics”). Enecsys aimed to commercialise

Amaratunga and his team's solar PV research. All relevant DoEng intellectual property was assigned to Enecsys. Amaratunga continued as Chairman until 2009, when the first round of venture capital funding was completed. He remained as a Director until October 2010.

Enecsys won initial funding from Cambridge Enterprise (2005), the East of England Development Agency (2004 and 2008) and the Carbon Trust 2008. Enecsys funded further research in the DoEng, while Enecsys worked in parallel to develop micro-inverter products. Enecsys has 36 issued patents of which 13 have been granted in the US, a further 5 have been allowed, with 39 pending (2013) (Ref 7).

Enecsys made sufficient progress with initial product development to win A-round funding of GBP9M in November 2009 from Wellington Partners, Good Energies and NES partners. The funding supported the development and launch of three market-ready micro-inverter products: the single micro-inverter (one inverter per solar PV panel), the monitoring system and communications gateway. These were launched into the European and North American markets in June 2010.

Enecsys secured further B-Round funding of GBP25M in May 2011 from its existing investors and Climate Change Capital Partners, bringing the total investment in Enecsys during the REF period to GBP34M. The funding led to further product development and subsequent announcement of a dual micro-inverter (one inverter for every two solar PV panels) in 2011.

All of the Enecsys micro-inverter products are founded on the underpinning research that was undertaken in the DoEng. Enecsys reported its first revenue in March 2011. It achieved USD1.4M in this first year of sales, which grew to nearly USD11.7M in the financial year 2012/13. Enecsys has shipped more than 150,000 micro-inverter units between 2008 and 2013. In 2013, it employs 75 people based in three offices in Europe, North America and Asia-Pacific, which is an increase of 68 from the beginning of 2008. Enecsys has established distribution agreements with installers in: Australia, Austria, Belgium, Croatia, Denmark, France, Germany, Greece, Hungary, Italy, Luxembourg, Malta, Mexico, Netherlands, Spain, Switzerland, Turkey, UK, Canada, and USA (Ref 7).

These installers have achieved high-profile sales, for example, Afresh Energy Limited has completed solar PV installations on over 225 homes in the 2014 Commonwealth Games athletes' village in Glasgow using Enecsys micro-inverters (Ref 8).

Enecsys products offer benefits versus traditional string inverters for solar PV installations that were made possible by the underpinning DoEng research:

- Each individual solar PV panel can be controlled, so that the performance of the panel can monitored and optimised for maximum energy harvest. A domestic customer and Professor at Stanford University said of his Enecsys equipped domestic system: *"We decided to go with the Enecsys micro inverter system rather than a more old fashioned string inverter system because our roof situation here is pretty complex. We've got a lot of shade. We've got a complicated roofline. Concerns that would really make one these older systems impractical. The folks at Enecsys estimated that we would be able to cover about two thirds of our electricity needs with this installation. In practice, it turns out to be more like 90%"* (Ref 9)
- Installation is less complicated, faster and cheaper because the design and location of the PV array is not influenced by shade. PowerPac, a UK-distributor, states: *"The new Enecsys solar micro inverter solution is the latest breed of advanced solar technology delivering a simplified PV array design. The new solar micro inverter solution can now be installed on any available roof space due to its new and innovative design. Whereas older versions are more difficult to install, this one is a lot easier in comparison and therefore makes it faster and cheaper to implement"* (Ref 10). German PV system installer, Mini Joule, gives similar evidence: *"We trust Enecsys micro inverters, because the system is easy to install, it is totally 'plug-and-play' and for complex installations with shading there are no problems. And of course our clients love the monitoring system"* (Ref 9). Abakus Solar (USA) states: *"Enecsys Micro Inverters liberate installers from many previous shading-related constraints"* (Ref 11). An installation integrator based in Hawaii said, *"The Enecsys system allowed us to change the layout without having to*

get new parts to install the inverters" (Ref 11).

- Less maintenance is needed, while lifetime and reliability is increased, with Enecsys guaranteeing an operational lifetime for its inverters that matches the typical 25-year lifetime of the solar PV panels. Enecsys presents analysis of expected total lifetime maintenance costs for a typical installation that shows reduction from GBP3000 using string inverters to just GBP500 with Enecsys micro-inverters. PowerPac, a UK distributor notes that *"[Enecsys] maintenance levels are significantly less"* (Ref 10).
- Safety for system installers working at roof-top level is improved, because Enecsys micro-inverters eliminate the need for high DC voltages. The Managing Director of Powercon BV, who has 30 years' experience of the PV industry, said *"I've become aware of the safety issues affecting solar installations"* and chose Enecsys micro-inverters for the installation on his own house *"because the system is safer due to the lower operating voltages"* (Ref 9).

In addition to selling micro-inverters for permanent roof-top solar PV arrays, Enecsys has worked with PV-panel manufacturers to create plug-in solar power solutions in the home. The home owner sets up the solar PV panel and simply plugs it into a standard mains outlet in the house. The Enecsys micro inverter manages the conversion to alternating current and synchronisation with mains electricity. In this way, the home owner benefits from solar power substituting for grid power without any need for expensive, professional installation. These kits sold by retailers in the range from 200W to 1kW. Sales figures were not released (Ref 7).

The Global Cleantech Group, a leading global research and advisory firm focused on innovation in energy and the environment, listed Enecsys in its Global Cleantech 100 awards in each of 2010, 2011 and 2012 (Ref 12).

5. Sources to corroborate the impact (indicative maximum of 10 references)

7. Founder and now Principal Engineer at Enecsys can corroborate all information about Enecsys
8. Client page on Afresh Energy Limited website at http://afreshenergy.co.uk/clients
9. Corporate video on Enecsys website at http://www.enecsys.com/resources/videos/
10. Enecsys installers page on PowerPac Limited website at http://www.powerp.co.uk/enecsys-installers.html
11. Case studies page on the Enecsys website at http://www.enecsys.com/resources/case-studies/
12. Global Cleantech 100 at http://www.cleantech.com/global100/global-cleantech-100/