

**RESEARCH GRANTS COUNCIL
THEME-BASED RESEARCH SCHEME (TRS)**

Completion Report on Funded Project

(Must be submitted within 12 months of the approved project completion date)

Project start date: September 2012
Project completion date: August 2017

1. Project Title: Sustainable Lighting Technology: From Devices to Systems

2. Names and Academic Affiliations of Project Team Members[#]

Project team member	Name / Post	Unit / Department / Institution	Average number of hours per week spent on this project in the <u>whole</u> project period
Project Coordinator (PC)	HUI Shu Yuen Ron Chair Professor	Dept. Electrical & Electronic Engineering, HKU	15
Co-Principal Investigator(s)	CHOI Hoi Wai Anthony Associate Professor	Dept. Electrical & Electronic Engineering, HKU	15
	TSE Chi Kong Michael Chair Professor	Dept. of Electronic & Information Engineering, PolyU	15
	WAFFENSCHMIDT Eberhard Chair Professor	Cologne University of Applied Sciences, Germany (formerly with Philips Solid	9

		State Lighting - until 2011)	
Co-Investigator(s)	LEE Chi Kwan Assistant Professor	Dept. Electrical & Electronic Engineering, HKU	
	TAN Siew Chong Associate Professor	Dept. Electrical & Electronic Engineering, HKU	
	WONG Siu Chung Associate Professor	Dept. of Electronic & Information Engineering, PolyU	
	LAI Yuk-Ming Associate Professor	Dept. of Electronic & Information Engineering, PolyU	
Collaborators			N.A.
			N.A.

Please highlight the approved changes in the project team composition and quote the date when the RGC granted approval of such changes. For changes in the project team composition, please submit a separate request, together with the justification and the curriculum vitae of the new member(s), to the RGC three months prior to the intended effective date of the change.

3. Project Objectives

Summary of objectives addressed/achieved:

Objectives*	Percentage achieved	Remarks**
1. An integrated and comprehensive study of new sustainable lighting technology (linking LED device theory to LED System Theory & Designs) that can (i) drastically reduce electronic waste while maintaining high energy efficiency and luminous efficacy, (ii) outperform existing lighting technology that meets the sole energy-saving criterion specified by Energy-Star program and (iii) reduce heat generation within buildings and greenhouse gas emission due to energy saving.	100	<p>The only change in the objective is to remove the study of the self-cooling heatsinks, as advised by the RGC panel.</p> <p>The HKU/PolyU/Cologne team members have jointly conducted a comprehensive review on LED driver topologies. We have successfully completed a classification and developed a design guideline for lighting industry. This comprehensive output just appeared a 14-page paper in the IEEE Transactions on Power Electronics in 2016 (cited over 68 times by June 2018).</p> <p>Sustainable driving circuits for LED and fluorescent lamps have been developed. These drivers satisfy the 3 criteria of energy saving, long product lifetime and recyclability. The designs of these sustainable LED lighting technologies are</p>

Objectives*	Percentage achieved	Remarks**
		<p>supported by the photo-electro-thermal (PET) theory for LED system.</p> <p>The linking of the “devices”, “drivers” and “system theory” remains the core component of this TRS project.</p>
<p>2. Practical realization of</p> <ul style="list-style-type: none"> • Improved LED device structure & packaging with improved efficacy & lifetime. • Optimally staggered device distribution for improved thermal & luminous performance. • New LED drivers with lifetime >10 years with the possibility of having over 80% of product material recyclable. • Sustainable lighting principle and design guidelines for lighting industry. 	<p>100</p>	<p>New LED structures (including the world’s first flexible LED strip) have been developed. These “devices” have been studied within the framework of the PET “System” Theory.</p> <p>The distribution of the staggered devices has been optimized and a model for designing such system has been developed and published.</p> <p>Electronic LED drivers and passive LED drivers without electrolytic capacitor have been developed. The later design has been adopted by industry and has reached production stage.</p> <p>Sustainable lighting design guideline for LED systems has been developed and published.</p>
<p>3 Deliverables:</p> <ul style="list-style-type: none"> • New LED theory linking the device characteristics and systems (i.e. devices, drivers, control and thermal design) for system design & optimization. • New single- and multi-chip LED device structures & manufacturing processes for improved photometric & lifetime performance. • New LED drivers & control techniques for meeting the 3 sustainable criteria • New LED System Design & Optimization tools for lighting industry • Patents and research papers. <p>*Trained research students and staff</p>	<p>100</p>	<p>The PET System Theory has exceeded its original links of (i) Heat, (ii) Light and (iii) Power to include (iv) Color. Based on this breakthrough, new precise dimming and color control techniques have been developed and filed for patents.</p> <p>The extended System Theory has allowed us to design new LED systems with multiple chips. A text book on this LED System Theory was published by Cambridge University Press in Sept. 2017.</p> <p>Besides the two patent-pending technologies on Passive LED Street Lighting (transferred to industry in Year 2 of the project), 4 more patent-pending technologies are in the process of being transferred to industry.</p> <p>The Passive LED Drivers have been manufactured and installed in China and Hong Kong since 2015 successfully. It</p>

Objectives*	Percentage achieved	Remarks**
		<p>also won the prestigious “ Prize of Patent Office Of Cooperation Council for THE ARAB STATES OF THE GULF” – GCCPO and a Special Gold Medal at the 46th Geneva International Exhibition of Inventions.</p> <p>Based on the work done in the first 4 years, over 8 patent applications have been filed. Among them, 3 patented technologies have been licensed, and 4 more are being negotiated between HKU and a high-tech company for technology transfer.</p> <p>Over 30 top-tier journal papers and 15 conference papers have been published. 14 publications are jointly published by two or more collaborating institutions.</p> <p>Both of HKU team and PolyU team have attracted funding for new LED projects based on the success of this TRS project.</p> <p>This TRS has supported 5 Ph.D, 1 MPhil students, as well as 9 research staff.</p>

* Please highlight the approved changes in objectives and quote the date when the RGC granted approval of such changes.

** Please provide reasons for significantly slower rate of progress than originally planned.

6. Research Highlights and Outputs

(Maximum 20 A4 pages for sections 6 to 11, excluding any appendices and attachments)

6.1 What are the most exciting research accomplishments of the project?

(Please list five or more of the team's best research accomplishments, such as journal and conference papers, software codes, research infrastructure, etc. For each item, please clearly justify how it has achieved international excellence (e.g. best paper award, invited presentation, citations, product licensed to industry, etc.))

The outcomes of this project have both *academic* and *industrial* impacts:

- (1) We have published a 14-page journal paper on: ““A Survey, Classification and Critical Review of Light Emitting Diode Drivers”, *IEEE Transactions on Power Electronics*, Vol. 31, No. 2, 2016, pp: 1503-1516”. This paper is a cornerstone paper on the principles and selection guide of LED drivers. It presents a family of LED drivers without using electrolytic capacitors. It is a significant contribution to both of the lighting research community and lighting industry. Since its publication in 2016, this paper has been cited 68 times by June 2018.
- (2) The Passive LED drivers have been transferred to industry in the 2nd year of the project and commercialized by the 3rd year. This invention is the world's first and only LED drivers that have efficiency > 90% AND lifetime > 10 years AND over 80% of the product materials recyclable. It has been installed in China and Hong Kong for four years. In 2018, it won the (i) The Prize of Patent Office Of Cooperation Council for THE ARAB STATES OF THE GULF – GCCPO and the Gold Medal with Special Recognition by the International Jury of Experts at the 46th Geneva International Exhibition of Inventions (2018)
- (3) 25 out of the 31 journal papers arising from this project were published in the IEEE Transactions on Power Electronics. This is the premium journal in this field with an impact factor of 7.2. The high number of journal papers in the same prestigious journal makes this TRS project highly visible in the international research community.
- (4) We have successfully extended the Photo-Electro-Thermal (PET) Theory for LED Systems to cover the four elements of light science (i.e. light, power, heat and color) within one mathematical framework. This is the world's first system theory for LED systems. Consequently, the PC received an invitation by Cambridge University Press to publish a book. This book was eventually published in September 2017.
- (5) In our first meeting with the Industrial Advisors, we were challenged to tackle the dimming and color control problems faced by the lighting industry. LED manufacturers use different binning systems and so there is no universally accepted binning systems. Even LEDs from the same manufacturers have large variations in terms of parameters. Responding to these challenges, we extended the PET Theory to cover color, and have successfully developed new technologies for precise dimming and color control of LED devices. These new technologies offer new and unprecedented dimming and color control precision of 1% and +/-30K, respectively (against existing 1% dimming and +/- 300K color control).
- (6) Regarding new LED structures, we have successfully developed the world's first flexible semiconductor-based LED device, and also new LED device with integrated

sensor in the same wafer. The latter development may open a door to high-end LED products with dimming and color control of high precision.

- (7) Based on the success of this TRS project, the HKU team has got a University-Industry Collaboration Fund to transfer the technology to industry, and the PolyU team has attracted an ITF project of \$6 Million on the use of LED technology for urban farming.

- 6.2 What was the added value of the TRS funding, rather than standard project grant funding? *(For example, could this work have been achieved with other funding scheme, such as the General Research Fund or Collaborative Research Fund? If not, why?)*

This project is the first one that successfully proven that we can design and manufacture truly sustainable LED drivers for lighting industry (meeting the criteria of high efficiency, long lifetime and recyclability).

Besides over 30 high-quality journal papers in top-tier journals, it has produced several patented and patent-pending technologies that have attracted industry for commercialization. It has successfully attracted the University-Industry Collaborative Grant, which allowed us to develop a working prototype as the basis for United Technologies Global Ltd. for production. Consequently, this company has marketed a series of passive LED drivers based on inventions rising from this project. These street lighting products have been installed in China and Hong Kong over the last 4 years and won a prestigious international invention award in Geneva in 2018.

Another technology transfer is our Single-Input-Multiple-Outputs LED driver technology, which has been adopted by Zyne Ltd. A licence agreement has been signed by HKU and Zyne to commercialize this technology for a range of lighting products.

- 6.3 If the project has not met its original objectives, why?
N.A.

- 6.4 (a) Peer-reviewed journal publication(s) arising directly from this project:
(Please attach a copy of the publication and/or the letter of acceptance if not yet submitted in the previous progress report(s). All listed publications must acknowledge RGC's funding support by quoting the specific grant reference. Please mark the symbol "#" next to the publications involving inter-institutional collaborations)

The Latest Status of Publications				Author(s) <i>(denote the corresponding author with an asterisk*)</i>	Title and journal/book <i>(with the volume, pages and other necessary publishing details specified)</i>	Submitted to the RGC <i>(indicate the year ending of the relevant progress report)</i>	Attached to this report <i>(Yes or No)</i>	Acknowledged the support of RGC <i>(Yes or No)</i>	Accessible from the institutional repository <i>(Yes or No)</i>
Year of publication	Year of acceptance <i>(for paper accepted but not yet published)</i>	Under review	Under preparation <i>(optional)</i>						

The Latest Status of Publications				Author(s) (denote the corresponding author with an asterisk*)	Title and journal/book (with the volume, pages and other necessary publishing details specified)	Submitted to the RGC (indicate the year ending of the relevant progress report)	Attached to this report (Yes or No)	Acknowledged the support of RGC (Yes or No)	Accessible from the institutional repository (Yes or No)
Year of publication	Year of acceptance (for paper accepted but not yet published)	Under review	Under preparation (optional)						
2014 (J1)				S. Li and S.Y.R. Hui*	"Self-configurable current-mirror circuit with short-circuit and open-circuit fault tolerance for balancing parallel light-emitting diode (LED) string currents", <i>IEEE Transactions on Power Electronics</i> , Vol. 29, No.10, October 2014, pp: 5498-5507	2015	No	Yes	Yes
2014 (J2)				X. Qu, S.C. Wong and C.K. Tse*	"A current balancing scheme with high luminous for high power LED lighting," <i>IEEE Transactions on Power Electronics</i> , vol. 29, no. 6, pp. 2649-2654, June 2014	2015	No	yes	yes
2014 (J3)				H.T. Chen and S.Y.R. Hui*	"Dynamic Prediction of Correlated Color Temperature and Color Rendering Index of Phosphor-Coated White Light-Emitting Diodes", <i>IEEE Transactions on Industrial Electronics</i> , Vol. 61, No.2, Feb., 2014, pp: 784-797	2015	No	yes	yes
2014 (J4)				H.T. Chen, S.C. Tan and S.Y.R. Hui*	"Color Variation Reduction of GaN-Based White Light-Emitting Diodes via Peak-Wavelength Stabilization", <i>IEEE Transactions on Power Electronics</i> , Vol.29, No.7, July 2014, pp: 3709-3719	2015	No	yes	yes
2014 (J5)				H.T. Chen, D. Lin, S.Y.R. Hui* and S.C. Tan	"Chromatic, photometric and thermal modeling of LED systems with non-identical LED devices", <i>IEEE Transactions on Power Electronics</i> , Vol. 29, Issue 12, 2014, pp: 6636-6647	2015	No	Yes	Yes

The Latest Status of Publications				Author(s) (denote the corresponding author with an asterisk*)	Title and journal/book (with the volume, pages and other necessary publishing details specified)	Submitted to the RGC (indicate the year ending of the relevant progress report)	Attached to this report (Yes or No)	Acknowledged the support of RGC (Yes or No)	Accessible from the institutional repository (Yes or No)
Year of publication	Year of acceptance (for paper accepted but not yet published)	Under review	Under preparation (optional)						
2014 (J6)				JY.F. Cheung, K.H. Li, R.S.Y. Hui and H.W Choi*	"Observation of enhanced visible and infrared emissions in photonic crystal thin-film light-emitting diodes", <i>Applied Physics Letters</i> , Volume: 105, Issue: 7, 2014 , Page(s): 071104- 071104-4	2015	No	Yes	Yes
2015 (J7)				Sinan Li, H.T. Chen, S.C. Tan, S.Y.R. Hui* and E. Waffenschmidt	# [Joint paper] "Power Flow Analysis and Critical Design Issues of Retrofit Light-Emitting Diode (LED) Light Bulb", <i>IEEE Transactions on Power Electronics</i> , Vol.30, No.7, 2015, pp: 3830-3840	2015	No	Yes	Yes
2015 (J8)				X. Qu, W. Zhang, S-C. Wong, and C.K. Tse*	"Design of a Current-Source-Output Inductive Power Transfer LED Lighting System", <i>IEEE Journal of Emerging and Selected Topics in Power Electronics</i> , Vol.3, No.1, 2015, pp: 306-314	2015	No	Yes	Yes
2015 (J9)				H. T. Chen; S. C. Tan; S. Y. R. Hui*	"Analysis and Modeling of High-Power Phosphor-Coated White Light-Emitting Diodes With a Large Surface Area", <i>IEEE Transactions on Power Electronics</i> , 2015, Volume: 30, Issue: 6, Pages: 3334 - 3344	2016	No	Yes	Yes
2015 (J10)				Sinan Li, G. Zhu, S.C. Tan and S.Y.R. Hui*	"Direct AC/DC Rectifier with Mitigated Low-Frequency Ripple Through Waveform Control", <i>IEEE Transactions on Power Electronics</i> , Vol.30, No.8, 2015, pp: 4336-4348	2015	No	Yes	Yes

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Year of publication	Year of acceptance (for paper accepted but not yet published)	Under review	Under preparation (optional)						
2015 (J11)				H.T. Chen, Y.F. Cheung, H.W. Choi, S.C. Tan and S.Y.R. Hui*	"Reduction of Thermal Resistance and Optical Power Loss Using Thin-Film Light-Emitting Diode (LED) Structures", <i>IEEE Transactions on Power Electronics</i> , Vol. 62, No. 11, 2015, pp: 6925-6933	2016	No	Yes	Yes
2015 (J12)				W.M. Ng and S.Y.R. Hui*	"Ultra-low-loss Passive T5 Fluorescent Lamp Ballasts for Subzero Temperature Operation", <i>IEEE Transactions on Power Electronics</i> , Vol. 30, Issue 10, 2015, pp: 5792-5799	2016	No	Yes	Yes
2015 (J13)				C. S. Wong, K. H. Loo, Y. M. Lai, and C. K. Tse*	"Low-current ripple LED driver by two-phase driving approach", <i>IET Electronics Letters</i> , 22 Oct. 2015, Vol51, No.22, pp: 1804-1806	2016	No	Yes	Yes
2015 (J14)				H.T. Chen, S.C. Tan and S.Y.R. Hui*	"Nonlinear Dimming and Correlated Color Temperature Control of Bi-Color White LED Systems", <i>IEEE Transactions on Power Electronics</i> , Vol. 30, No. 12, 2015, pp: 6934-6947	2016	No	Yes	Yes
2015 (J15)				W.S Cheung., Y.F. Cheung, H.T. Chen, S.Y.R. Hui, E. Waffenschmidt & H.W. Choi*	# [Joint paper] "InGaN Light-emitting Diode Stripes with Reduced Luminous Exitance", <i>Optics Express</i> , 2015, v. 23, p. 15021-15028	2016	No	Yes	Yes
2015 (J16)				X. Qu, S.C. Wong and C.K. Tse*	"An improved LCLC current-source-output multi-string LED driver with capacitive current balancing," <i>IEEE Transactions on Power Electronics</i> , 2015, Volume: 30, Issue: 10, Pages: 5783 - 5791	2016	No	Yes	Yes

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Year of publication	Year of acceptance (for paper accepted but not yet published)	Under review	Under preparation (optional)						
2015 (J17)				K. H. Li, Y. F. Cheung, and H. W. Choi	"Whispering gallery mode lasing in optically isolated III-nitride nanorings", <i>Optics Letters</i> Vol. 40, pp. 2564-2567 (2015)	2016	No	Yes	Yes
2016 (J18)				S. Li, S.C. Tan, C.K. Lee, E. Waffenschmidt, S.Y.R. Hui* and C.K., Tse	# [Joint paper] "A Survey, Classification and Critical Review of Light Emitting Diode Drivers", <i>IEEE Transactions on Power Electronics</i> , Vol. 31, No. 2, 2016, pp: 1503-1516	2016	No	Yes	Yes
2016 (J19)				C.S. Wong, K.H. Loo, Y.M. Lai, M.H.L. Chow, C.K. Tse*	"An Alternative Approach to LED Driver Design Based on High-Voltage Driving", <i>IEEE Trans. on Power Electronics</i> , 2016, Volume: 31, Issue: 3, Pages: 2465 – 2475	2016	No	Yes	Yes
2016 (J20)				A. Lee, H.T. Chen, S.C. Tan and S.Y.R. Hui*	"Precise dimming and color control of LED systems based on color mixing", <i>IEEE Transactions on Power Electronics</i> , Vol.31, No.1, 2016, pp: 65-80	2016	No	Yes	Yes
2016 (J21)				H. Chen, C.H. Choy and S.Y.R. Hui*	"Characterization, Modeling and Analysis of Organic Light-Emitting Diodes with Different Structures", <i>IEEE Transactions on Power Electronics</i> , Vol.31, No.1, 2016, pp: 581-592	2016	No	Yes	Yes
2016 (J22)				Y. Guo, S. Li, S.C. Tan, C.K. Lee and S.Y.R. Hui*	# [Joint Paper] "Single-stage AC/DC Single-Inductor Multiple-Output (SIMO) LED Drivers", <i>IEEE Transactions on Power Electronics</i> , Volume: 31, Issue: 8, 2016, Pages: 5837-5850	2016	No	Yes	Yes

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Year of publication	Year of acceptance (for paper accepted but not yet published)	Under review	Under preparation (optional)						
2016 (J23)				H. Wu, S.C. Wong, C.K. Tse* and Q. Chen	"Control and modulation of bidirectional single-phase AC-DC three-phase-leg SPWM converters with active power decoupling and minimal storage capacitance," <i>IEEE Transactions on Power Electronics</i> , Vol.31, No.6, June 2016, pp: 4226-4240	2016	No	Yes	Yes
2017 (J24)				Sinan Li*; Wenlong Qi; Siew-Chong Tan; S. Y. (Ron) Hui	"Integration of an Active Filter and a Single-Phase AC/DC Converter With Reduced Capacitance Requirement and Component Count", <i>IEEE Transactions on Power Electronics</i> , Year: 2016, Volume: 31, Issue: 6, Pages: 4121 – 4137	2018	Yes	Yes	Yes
2017 (J25)				JC. S. Wong*, K. H. Loo, Y. M. Lai, M. H. L. Chow and C. K. Tse	"Accurate capacitive current balancing in multistring LED lighting systems based on switched-capacitor-controlled LCC resonant network," <i>IEEE Transactions on Power Electronics</i> , Year: 2017, Volume: 32, Issue: 3, Pages: 2167 - 2179	2018	Yes	Yes	Yes
2017 (J26)				Huan-Ting Chen; Siew-Chong Tan; Albert Lee; De-Yan Lin; S. Hui*	"Precise Color Control of Red-Green-Blue Light-Emitting Diode Systems", <i>IEEE Transactions on Power Electronics</i> , Year: 2017, Volume: 32, Issue: 4, Pages: 3063 - 3074	2018	Yes	Yes	Yes

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Year of publication	Year of acceptance (for paper accepted but not yet published)	Under review	Under preparation (optional)						
2017 (J27)				Sinan Li*; Yue Guo; Siew-Chong Tan; S. Y. Hui	# [Joint paper] “An Off-Line Single-Inductor Multiple-Outputs LED Driver with High Dimming Precision and Full Dimming Range”, <i>IEEE Transactions on Power Electronics</i> , Year: 2017, Volume: 32, Issue: 6, Pages: 4716 - 4727	2018	Yes	Yes	Yes
2018 (J28)				Hao Wu; Siu-Chung Wong*; Chi K. Tse; S. Y. Ron Hui; Qianhong Chen	# [Joint paper] “Single-Phase LED Drivers With Minimal Power Processing, Constant Output Current, Input Power Factor Correction, and Without Electrolytic Capacitor”, <i>IEEE Transactions on Power Electronics</i> , Year: 2018, Volume: 33, Issue: 7, Pages: 6159 - 6170	2018	Yes	Yes	Yes
2018 (J29)				C. S. Wong; K. H. Loo; Herbert Ho-Ching Iu; Y. M. Lai; Martin H. L. Chow; Chi K. Tse*	“Independent Control of Multicolor Multistring LED Lighting Systems With Fully Switched-Capacitor-Controlled LCC Resonant Network”, <i>IEEE Transactions on Power Electronics</i> , Year: 2018, Volume: 33, Issue: 5, Pages: 4293 – 4305	2018	Yes	Yes	Yes
2018 (J30)	2017			Hao Wu; Siu Chung Wong*; Chi K. Tse; Qianhong Chen	“A PFC Single-Coupled-Inductor or Multiple-Output LED Driver Without Electrolytic Capacitor”, <i>IEEE Transactions on Power Electronics</i> (early access)	2018	Yes	Yes	Yes

The Latest Status of Publications				Author(s) (denote the corresponding author with an asterisk*)	Title and journal/book (with the volume, pages and other necessary publishing details specified)	Submitted to the RGC (indicate the year ending of the relevant progress report)	Attached to this report (Yes or No)	Acknowledged the support of RGC (Yes or No)	Accessible from the institutional repository (Yes or No)
Year of publication	Year of acceptance (for paper accepted but not yet published)	Under review	Under preparation (optional)						
2018 (J31)	2017			Zheng Dong; Chi K. Tse*; S. Y. Ron Hui,	# [Joint paper] “Current-Source-Mode Single-Inductor Multiple-Output LED Driver with Single Closed-Loop Control Achieving Independent Dimming Function”, IEEE Journal of Emerging and Selected Topics in Power Electronics , Year: 2018, (Early Access)	2018	Yes	Yes	Yes

(b) Recognised international conference(s) in which paper(s) related to this project was/were delivered:

(Please attach a copy of each conference abstract)

Month/Year/Place	Title	Conference name	Submitted to the RGC (indicate the year ending of the relevant progress report)	Attached to this report (Yes or No)	Acknowledged the support of the RGC (Yes or No)	Accessible from the institutional repository (Yes or No)
Sept/2013/ Denver USA (C1)	# [Joint Paper] “A review and classification of LED ballasts”	IEEE Energy Conversion Congress & Exposition	2014	No	Yes	Yes
Nov/2013 Vienna (C2)	“A current balancing scheme with high luminous efficiency for high power LED lighting.”	IEEE Industrial Electronics Conference	2014	No	Yes	Yes
March/2014 Fort Worth USA (C3)	# [Joint Paper] “Critical design issues of retrofit light-emitting diode (LED) light bulb”	IEEE Applied Power Electronics Conference	2014	No	Yes	Yes
Sept/2014 Pittsburgh USA (C4)	“Design consideration of a current-source-output inductive power transfer LED lighting system”	IEEE Energy Conversion Congress & Exposition	2015	No	Yes	Yes
Aug/2014 Lappeenranta Finland (C5)	“Elimination of electrolytic capacitor in LED power supplies by two-phase driving approach”	European Power Electronics Conference	2016	No	Yes	Yes
March/2015 Charlotte USA (C6)	"Analysis, control and design of a long-lifetime ac-dc bus converter within a nanogrid"	IEEE Applied Power Electronics Conference	2016	No	Yes	Yes

Month/Year/ Place	Title	Conference name	Submitted to the RGC (<i>indicate the year ending of the relevant progress report</i>)	Attached to this report (<i>Yes or No</i>)	Acknowledged the support of the RGC (<i>Yes or No</i>)	Accessible from the institutional repository (<i>Yes or No</i>)
March/2015 Charlotte USA (C7)	# [Joint Paper] "Reset-sensing quasi-V2 single-inductor multiple-output buck converter with reduced cross-regulation"	IEEE Applied Power Electronics Conference	2016	No	Yes	Yes
Sept/2015 Montreal Canada (C8)	"Non-linear feedback control of robust bi-color LED lighting"	IEEE Energy Conversion Congress & Exposition	2016	No	Yes	Yes
Sept/2015 Bregenz Austria (C9)	# [Joint Paper] "Reliable and cost effective LED drivers improving perception artefacts and grid compatibility"	5th LED professional Symposium and Expo (LpS 2015)	2016	No	Yes	Yes
Apr/2015 Yokohama Japan (C10)	[Invited Paper] "Novel LED Geometries Enabled by Advanced Laser Processes"	3 rd International Conference on Light-emitting diode and their Industrial Applications	2016	No	Yes. Acknowledgement was given in the invited talk.	Yes
Aug/2015 Beijing China (C11)	"Photo-electro-vibrational- thermal Characterization of Epi-flexible GaN Light-emitting Diodes"	International Conference on Nitride Semiconductors	2016	No	Yes	Yes
Mar/2016 San Francisco USA (C12)	Emission characteristics of light-emitting diodes by confocal microscopy	<i>Proc. SPIE</i> 9768, Light-Emitting Diodes: Materials, Devices, and Applications for Solid State Lighting	2016	No	Yes	Yes
May/2016 Yokohama Japan (C13)	"GaN light-emitting diode with monolithically-integrated photodetector"	4th International Conference on Light-Emitting Devices and Their Industrial Applications	2016	No	Yes	Yes

(c) RGC funding should have been acknowledged in all publication(s)/conference papers listed in (a) and (b) above. If no acknowledgement has been made in any of the publications/ papers, please indicate and provide explanations.

Nil.

6.5 To what extent this project has strengthened inter-institutional collaborations and other partnerships?

In this project, the HKU, PolyU and Cologne teams have produced over 30 journal papers and 15 conference papers. Among these research publications, 13 of them are joint publications.

After this TRS project, the HKU and the PolyU teams jointly submitted a renewal TRS application in 2017, although the application was not successful. However, they submitted another TRS proposal on Wireless Power in 2018. This strong collaboration is expected to

continue in the foreseeable future.

Prof. Eberhard Waffenschmidt of Cologne University and Dr. CK Lee of HKU have obtained RGC HKU-Germany Research Grant to continue their work.

6.6 Research students trained (registration/awards):

Name	Degree registered for	Date of registration	Date of thesis submission/ graduation
Sinan LI	Ph.D (HKU)	July 2011	Graduated in Dec 2015
Raymond W.M. NG	Ph.D (HKU)	July 2011	Graduated in Dec 2015
Chi Sing WONG	Ph.D (PolyU)	Sept. 2013	Graduated in Dec 2017
Hao WU	Ph.D (PolyU)	Sept. 2013	Graduated in Dec 2017
Feng CONG	Ph.D (HKU)	Sept. 2012	Graduated in Dec 2016
Wing Shing CHEUNG	MPhil (HKU)	Sept. 2013	Graduated in Dec. 2015

6.7 Specific products (e.g. software or netware, instruments or equipment developed):

Passive LED Drivers for Street Lighting Systems have been commercialized by United Technologies Global Ltd. and marketed through its subsidiary Federal Group Limited.

6.8 Other education activities and/or training programmes developed:

- TRS Workshop (Feb. 2014) for the Public and Industry in Hong Kong
 - Final-year projects based on research topics of this TRS project. [One final-year student met the TRS Review Panel members in August 2014].
 - Introductory Workshop on Sustainable LED Street Lighting for the Electrical & Mechanical Services Department and Highway Department of the HK SAR Government [February 2016] – eventually, our Passive LED Street Lighting has been adopted.
 - Two exchange students from Cologne University had the summer internships at HKU in July-August 2015.
 - HKIE and IEEE Workshop on Sustainable Lighting Technology June 2017 (to present the outcomes of this projects to over 200 attendees from industry and government departments)
 - TRS Symposium Dec. 2017 (to the general public).
 - Conference Tutorial (3 hours): “Photo-Electro-Thermal Theory for LED Systems and its Applications”, by Prof. Ron Hui and Prof. SC Tan, IEEE Energy Conversion & Exposition (IEEE ECCE) 2018, Portland, Oregon, USA Sept., 2018
-

6.9 Please highlight any deliverables indicated in the project implementation timetable endorsed

by the RGC which have not been covered or achieved as per sections 6.1 to 6.8 above, and explain/ elaborate.

We have completed our project plan within the first 4 years, and are grateful that the TRS review panel encouraged us to explore new ideas in the 5th year.

Project Management

6.10 Please elaborate how the PC has played his/her role in coordinating and managing the project.

The PC has played a leadership role in setting up and chairing all meetings over the last 5 years. He also directs the 3 research teams to focus on their respective projects based on the project plans and objectives.

Besides holding large meetings (such as Annual Meeting with researchers and Annual Meeting with external advisors), he organises joint research meetings and laboratory visits so that team members from different universities can have more interactions and idea exchanges. He hold regular meetings and telephone/skype meetings with the Co-PIs to discuss the progress and plans of this TRS project. These frequent meetings ensure timely responses can be made to sort out issues and speed up the progress.

One important aspect of managing a large TRS project is financial control. The PC is delighted to report that the financial situation of this TRS project is prudent and sound.

In terms of research outputs, the PC insists on publishing the research outputs only at the top-tier journals. He has been successful in controlling the high quality of the research publications and persuading all team members to do so. For the “Drivers” and “System” aspects of this TRS project, we have been able to publish most of our journal papers in the IEEE Transactions on Power Electronics (Impact Factor > 7.2) and IEEE Transactions on Industrial Electronics (Impact Factor > 7.2). These two journals are among the top 5 IEEE journals in terms of impact factors.

The PC also plays an active role in promoting the outputs of this TRS project to the public and lighting industry. These efforts have paid off because we have attracted ITF funding, substantial technology transfer (6 out of 9 patent applications adopted by industry), new sustainable LED street lighting products, thus bringing benefits to society (as expected from a TRS project).

A Management Board comprising two external industrial advisors, Mr. Mike Mastroyannis (formerly with Traxon Ltd.) and Dr. Sun Tam (formerly with OptiLED), the overseas Co-PI Professor Eberhard Waffenschmidt, the HKU and PolyU team members has played an instrumental role in the success of this TRS project.

Over the last 5 years, several important ideas have been suggested by the external advisors and followed up by the research teams. Examples are:

- The challenge and importance of precise dimming and color control.
 - (We have responded to this challenged and come up with several patent-pending technologies – which are being discussed for technology transfer).
- The need for integrating photo-sensors into LED device wafers in order to ensure precise color control taking into long-term ageing into consideration,
 - (We have responded by starting a new project in this direction.)

For the last 5 years, we have held the following meetings:

- Dec. 2012: First Annual Meeting with all researchers and Industrial Advisors
 - July 2013: Meeting for HKU and PolyU leaders
 - Sept. 2013 Annual meeting with Industrial Advisors and Overseas Co-PI
 - Feb. 2014: Meeting for HKU and PolyU leaders.
 - March 2014: Special joint research group meeting in IEEE APEC, Fort Worth, Texas.
 - August 2014: Special meeting with the RGC Panel Members (Review Panel)
 - 25 Jun 2015: Joint research meetings at HKU.
 - 9 Sept 2015: Annual Meeting with researchers
 - 10 Sept. 2015: Annual Meeting with Industrial Advisors and Overseas Co-PI
 - 27 Nov 2015: Team Leaders meeting (to discuss renewal plan of this TRS project)
 - 14 Jan. 2016: Team Leaders meeting (to discuss a joint conference paper)
 - 12 Apr 2016: A laboratory visit and meeting at the PolyU laboratory
 - 20 June 2016 Annual Meeting with all researchers
 - 25 June 2016 TRS review meeting with RGC panel
 - 20 April 2017 A laboratory visit and meeting at the PolyU laboratory
 - 17 June 2019 Annual meeting with all researchers
 - 20 June 2017 Joint HKIE and IEEE Workshop on Sustainable Lighting
 - 23 Nov. 2017 Meeting for team leaders
 - 9 Dec 2017 RGC Theme-based Research Scheme (TRS) 2nd Public Symposium 2017
 - 21 June 2018 Concluding meeting for all researchers
-

7. Awards and Recognition

- 7.1 Have any research grants been awarded that are directly attributable to the results obtained from this project?

University-Industry Matching Grant for Joint Research: : UIM/231 \$ 244,550

Industrial Partner: United Technologies Global Ltd.

Research & Development of high-power LED Street Lighting Systems based on Passive LED Drivers 01/6/2013 – 28/02/ 2014

- 7.2 Have any project team members participated as invited speakers in or organisers of international conferences as a result of this project?

Dr. H.W. Choi:

Invited paper: “Novel LED Geometries Enabled by Advanced Laser Processes”

3rd International Conference on Light-emitting diode and their Industrial Applications

Apr/2015, Yokohama Japan

- 7.3 Have any project team members taken leadership positions in editorial boards, scientific and professional organisations?

Prof. Ron Hui:

Editor, IEEE Journal of Emerging and Selected Topics in Power Electronics

Associate Editor, IEEE Transactions on Power Electronics

Associate Editor, IEEE Transactions on Industrial Electronics

Prof. C.K. Tse:

Editor-in-Chief, IEEE CAS Society Newsletter (2007-)

Editor, International J. Circuit Theory and Applications (2008-)

Honorary Member of Editorial Board, International J. Bifurcation and Chaos (2010-)

Associate Editor, IEEE Journal of Selected and Emerging Topics in Power Electronics (2013-)

Associate Editor, IEEE TRANSACTIONS ON POWER ELECTRONICS (1999-)

Associate Editor, International J. Systems Science (2002-)

Associate Editor, IEICE NOLTA Journal (2010-)

Prof. S.C. Tan:

Associate Editor IEEE Transactions on Power Electronics

Associate Editor, Cogent Engineering

Dr. C.K. Lee:

Associate Editor, IEEE Journal of Emerging and Selected Topics in Power Electronics

Dr. S.C. Wong:

Associate Editor, IEEE TRANSACTIONS ON CIRCUITS AND SYSTEMS Part II (2016-)

Editorial Board, Energy and Power Engineering journal

Editorial Board, Journal of Electrical and Control Engineering

7.4 Any documentary proof of the application of technologies arising directly from this project?

The success of our Passive LED drivers has been widely reported in local media:

<http://news.rthk.hk/rthk/ch/component/k2/1399656-20180603.htm>

https://news.mingpao.com/pns/dailynews/web_tc/article/20180604/s00002/1528048606278

https://news.mingpao.com/ins/instantnews/web_tc/article/20180603/s00001/1528013489934

<https://www.am730.com.hk/news/%E6%96%B0%E8%81%9E/%E7%8D%B2%E7%8D%8E%E7%A7%91%E7%A0%94%E5%AF%A6%E5%9C%B0%E8%A9%A6%E8%A1%8C%E3%80%8C%E8%A2%AB%E5%8B%95%E5%BC%8Fled%E9%9B%BB%E6%BA%90%E3%80%8D%E8%B7%AF%E7%87%88%E6%9B%B4%E7%92%B0%E4%BF%9D-128512>

http://orientaldaily.on.cc/cnt/news/20180604/00176_047.html

7.5 Other awards and recognitions as a result of this project (please specify):

The invention of the Passive LED Driver has won the following:

- The Prize of Patent Office Of Cooperation Council for THE ARAB STATES OF THE GULF – GCCPO: 46th Geneva International Exhibition of Inventions (2018)
- Gold Medal with Special Recognition by the International Jury of Experts: 46th Geneva International Exhibition of Inventions (2018)

8. Impacts

- 8.1 What are the current and expected impacts of the project on the long-term development of Hong Kong (social or economic development, e.g. patent, technology transfer, collaboration with external organisations, etc.)?

Within the 5 years period, we have successfully transferred two groups of patented/pentent-pending technologies to lighting industry.

The first group of technologies involves Passive LED Drivers. Over 400 units have been installed in Heshan City and Hong Kong. With a record of no failure over the last 4 years, our Hong-Kong-based licensee has a new project of installing about 8000 units in China and a trial project in Hong Kong. The uniqueness of this invention includes its true sustainability nature and high robustness against extreme weather conditions. With over 180 million lampposts in major cities in China, the licensee expects to ramp up the production quickly within the next few years. After the release of this range of street lighting products, we have been invited to give seminars to the Highways Department and the Electrical & Mechanical Services Department of the HK SAR Government.

With over 150,000 lamp posts, Hong Kong will be a pioneer in adopting this sustainable lighting systems to showcase our inventions with environmentally friendly features. It is hoped that the example of HK in adopting true sustainable lighting technology will attract many mainland cities to follow.

The second group of technologies is related to the Single-input-multiple-outputs LED drivers. A start-up company has licensed this technology and is integrating it into smart lighting systems which combine both lighting technology and wireless communication together. The new smart lighting system can provide not only lighting and lighting energy control functions, but also people monitoring and guiding functions. It has been installed in a site of the Society for the Blinds to guide people with visual limitations to walk to their designations in a building.

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- 8.2 Others (please specify):

N.A.

9. Sustainability of the Project

- 9.1 Whether there are new ideas evolved directly from this project?

New ideas arising from this project include:

- The extension of the PET theory to cover color. Consequently, the four elements of LED technology (light, heat, power and color) are united within one mathematical framework.
- New LED drivers with high efficiency and long lifetime have been classified for a range of applications. We have provided lighting industry a guideline in the choice of driver circuits.

- New precise dimming and color control
- New idea of single-input-multiple-output LED drivers

9.2 Whether there are new projects evolved directly from this project?

- University-Industry Collaborative Project between United Technologies Global Ltd. and HKU, leading eventually to the production and commercialization of a range of passive LED drivers for street lighting.
- New commercial projects by licensee (United Technologies Global Ltd) in installing over 8000 passive LED drivers in China and in Hong Kong.
- New commercial projects by licensee (Zyne Ltd) in incorporating the single-input-multiple-outputs LED drivers in smart lighting systems.
- ITF Project led by PolyU on Urban Farming Systems with Automated LED and Intelligent Control since Sept. 2017
-

9.3 Whether there are new collaborations developed directly from this project?

United Technologies Global Ltd. and HKU have worked on a subsequent 3-phase Passive LED drivers for high-power lighting applications (such as public lighting in sports stadium). A patent application based on this collaboration has been filed through HKU.

9.4 Please give details on how much money and from which sources has been obtained/requested for the specific purpose of continuing the work started under this project.

United Technologies Global Ltd. has spent about HK\$ 2 million in filing patent applications on the Passive LED Drivers in 20 countries. They are marketing a range of passive LED driven street lighting systems in China, Hong Kong and Southeast Asia.

PolyU team has obtained an ITF project of \$6 Million on “Urban Farming Systems with Automated LED and Intelligent Control”.

10. Statistics on Research Outputs

(Please ensure the statistics in this section are consistent with the information presented in other sections of this report.)

	Peer-reviewed journal publications	Conference papers	Scholarly, books, monographs and chapters	Patents awarded	Other research outputs (please specify)	
No. of outputs arising directly from this research project	31	13	1	2 granted 6 pending	Type	No.
					Products	>2

12. The Layman's Summary

(describe in layman's language the abstracts and research impact of the project.)

This project is related to the “sustainability” of lighting systems (used in buildings and cities’ large-scale infrastructures such as road lighting) that consume 20% of electricity globally. Sustainable Lighting Technology proposed here deviates from the traditional Energy-Star concept which focuses only on energy saving. It stresses a new principle that includes (i) energy saving, (ii) long product lifetime and (iii) recyclability of product materials. It highlights the important point that “energy-saving technology is not necessarily environmentally-friendly if it generates lots of harmful electronic waste within a short product lifetime”.

The outcomes arising from this project involve both theoretical and industrial impacts. On the theoretical side, a General LED System Theory linking the interactions of heat, light, power and color within one mathematical framework has been established as a general design tool for LED systems. New LED drivers with high energy efficiency, long lifetime and recyclability have been identified. A comprehensive classification and design guidelines have been developed for lighting industry. On the industrial aspects, several technologies have been adopted and commercialized by lighting industry for production. This project has also led to both new Industrial Projects and ITF projects. The outcomes of this project have been disseminated in top-tier research journals, international conferences and public seminars organized by the Hong Kong Institution of Engineers, Institute of Electrical and Electronic Engineers and the Research Grant Council.

With several major lighting research centers based in Hong Kong and over 1000 LED product manufacturers in South China, this project is expected to bring significant benefits to Hong Kong and its nearby regions.