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A new approach to environmental impact studies and lifecycle assessments for horticultural lighting systems

K.Bertin¹, G.Zissis¹, P.Raynham², A.Moutsi³, S.A.Mucklejohn³ and B.Preston³

¹ Université Toulouse III - Paul Sabatier, LAPLACE, 118 route de Narbonne Bat 3R3, Toulouse cedex 9, France

² Institute for Environmental Design and Engineering, Central House, 14 Upper Woburn Place, London WC1H 0NN, UK

³ Ceravision Limited, 28 Tanners Lane, Blakelands, Milton Keynes MK14 5BN, UK

E-mail: bertin@laplace.univ-tlse.fr



Introduction

The authors introduce a new approach to quantifying the environmental impact and lifecycle assessments for horticultural lighting systems based on functional units expressed as the products of photosynthetic photon flux density (PPFD) ($\mu\text{mol}\cdot\text{m}^{-2}\cdot\text{s}^{-1}$) and time or irradiance ($\text{W}\cdot\text{m}^{-2}$) and time. The traditional functional unit used for assessing light sources, 1×10^6 lm.h, is not appropriate for horticultural applications as the lumen is a quantity based on the response of the human eye over the range 380 to 780 nm. The new assessments are based not on the output of the light source nor the light source plus the luminaire and electronic control gear but on the irradiance and uniformity delivered by the lighting installation to a defined surface for 1000 h. This approach reflects the importance of the lighting design as well as the characteristics of the light source, gear and luminaire.

Green house configuration

The area of the studied greenhouse is 50m x 81m. A plane surface has been used because the actual irradiance experienced by the plant varies as the plant grows and new leaf formation promotes shade to other parts of the plant. The properties of used material for wall, roof and floor are detailed in Table 1. We neglected the metallic frames parts of the greenhouse for these calculations.

	Material	Transmittance	Reflectance
Roof / Side walls	Polycarbonate plastic	90%	10%
Floor	Dirt	0%	20%

Table 1. Properties of the Greenhouse

Lighting Calculation & Simulation

- The amount lighting required was determined by calculating the fraction of the source flux falling onto the plants using an extension of the methods set out in CIE 40:1978 and uniformity of the light over the crop was controlled using the spacing to height ratio calculated according to the SLL Code for Lighting 2012. It was then possible to deduce the number of sources required to deliver $300\mu\text{mol}\cdot\text{s}^{-1}\cdot\text{m}^{-2}$ to the reference plane in the greenhouse. This calculation was done for a range of light sources including High Pressure Sodium (HPS) 1000W, Light Emitting Diode (LED) 285W and Metal Halide (MH) 1000W. (Table 2.)
- The mounting height is 2m.
- We use the dedicated Spectral Power Distribution (SPD) of each lamp (Chart 1.) to determine the average irradiance for several wavelength range over PAR, UV-A and Far Red. (Table 2.)
- We compared the results with a 3D modelling of the regarding configuration into Dialux 9.0 and validated our average illuminance and uniformity calculations (Chart 2.)

	Units	1000 W HPS	285W LED	1000 W MH	
Spacing	m	2,25	1,25	2	
Number	NA	864	2640	1066	
Unit power	W	1040	285	1040	
Useful lamp life*	h	9900	50000	3100	
PPFD	$\mu\text{mol}\cdot\text{s}^{-1}\cdot\text{m}^{-2}$	335,43	325,57	341,88	
Illuminance	lux	24515	18192	24504	
Uniformity	NA	0,56	0,95	0,74	
Power density	$\text{W}\cdot\text{m}^{-2}$	221,87	185,78	273,74	
Irradiance	UV-A (315-400 nm)	$\text{W}\cdot\text{m}^{-2}$	0,5319	0	4,8861
	Blue (400-500 nm)	$\text{W}\cdot\text{m}^{-2}$	3,5310	9,3898	26,645
	Green (500-600 nm)	$\text{W}\cdot\text{m}^{-2}$	27,175	21,646	39,325
	Red (600-700 nm)	$\text{W}\cdot\text{m}^{-2}$	30,937	30,147	10,318
	Far red (700-780 nm)	$\text{W}\cdot\text{m}^{-2}$	5,0005	1,2447	3,5034
	PAR (400-700 nm)	$\text{W}\cdot\text{m}^{-2}$	61,643	61,183	76,288
Energy per 1000h	MWh	898,56	752,4	1108,64	

Table 2. Lighting Calculation

*the useful lamp life is defined as the operating time for the product of Lamp Survival Factor (LSF) and Source Maintenance Factor (SMF) to reach 0.85

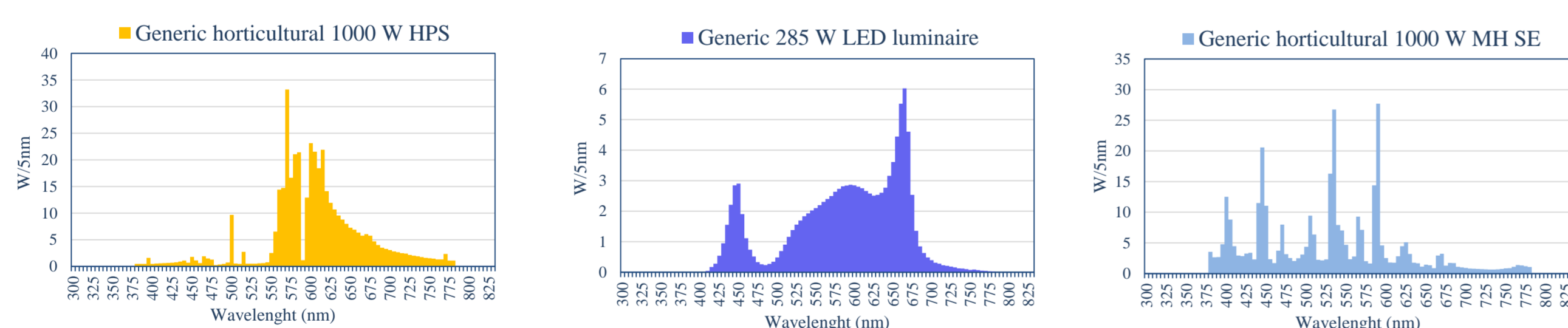


Chart 1. Lamps Spectral Power Distribution

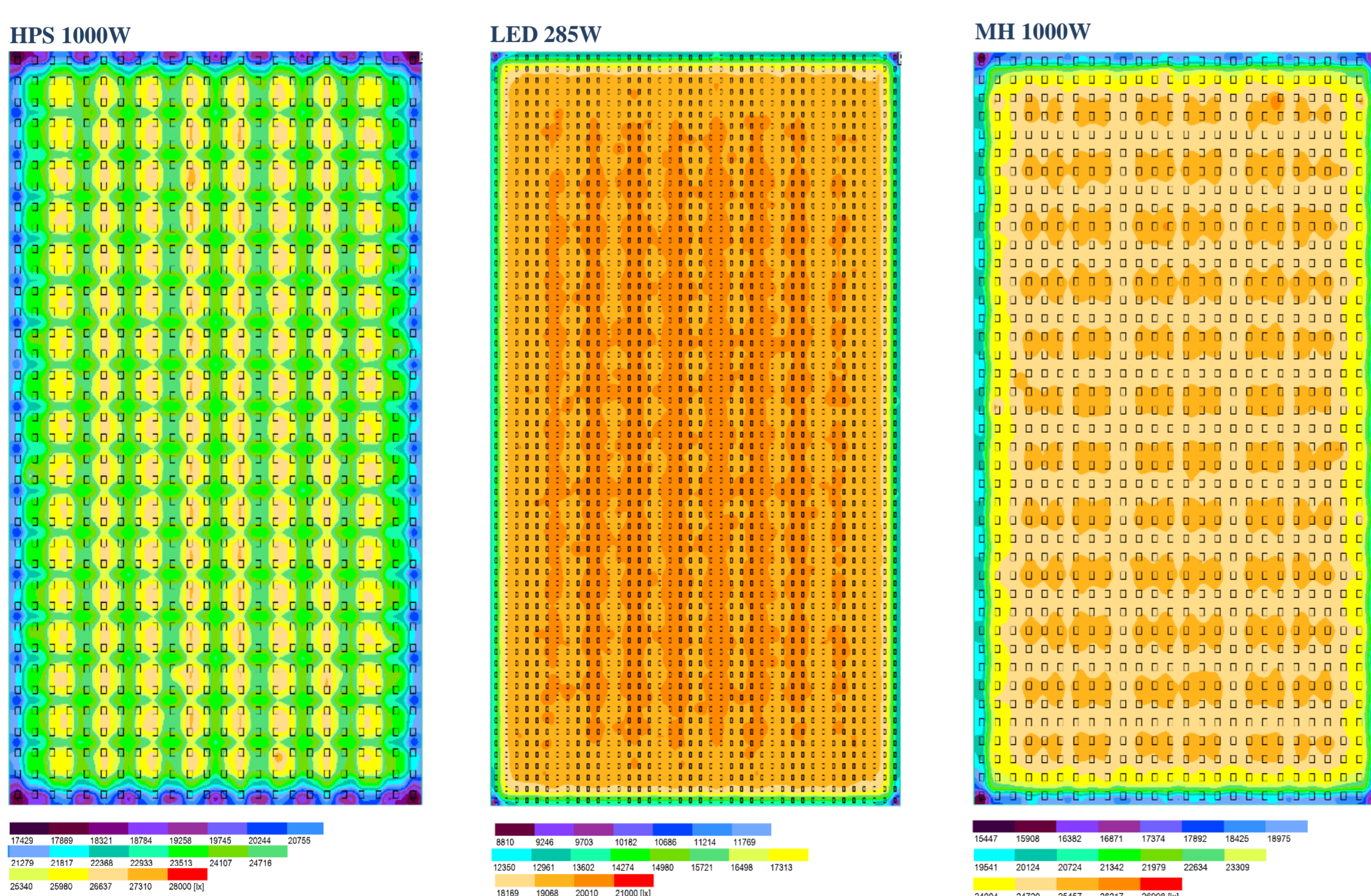


Chart 2 : Illuminance (lux), Uniformity and luminaire localization for HPS 1000W, LED 285W and MH 1000W – Spacing between measure point : 1m

Life Cycle Assessment (LCA) Methods & Results

- The LCA has been done thanks to Simapro 9 and EcoInvent 3.5. The calculation method is Recipe 2016 Endpoint with the Hierarchist perspective.
- Results are presented as a unique score expressed in KiloPoint. One point represents the potential environmental impacts for an average US citizen over 1 year.
- All phases of life cycle from material extraction to end of life, including transport and energy consumption, are considered.
- Lists of materials for lamps, luminaires and electronic control gear have been defined from dismantling and weighting all parts. When dismantling was not possible, inventories have been derived from products sheets from luminaires manufacturers or literature.
- The average LED component from EcoInvent has been used for LED luminaires.
- The useful lamp life is defined as the operating time for the product of Lamp Survival Factor (LSF) and Source Maintenance Factor (SMF) to reach 0.85.
- The UK electricity mix has been used for energy consumption during use phase.

Life Cycle Phase	Lamps		
	HPS	LED	MH
Materials and manufacturing	1,5	3	1,6
Use (energy consumption)	98,5	97	98,4
Others (Transport & End of life)	<0,1		

Table 3 : % of overall potential environmental impacts

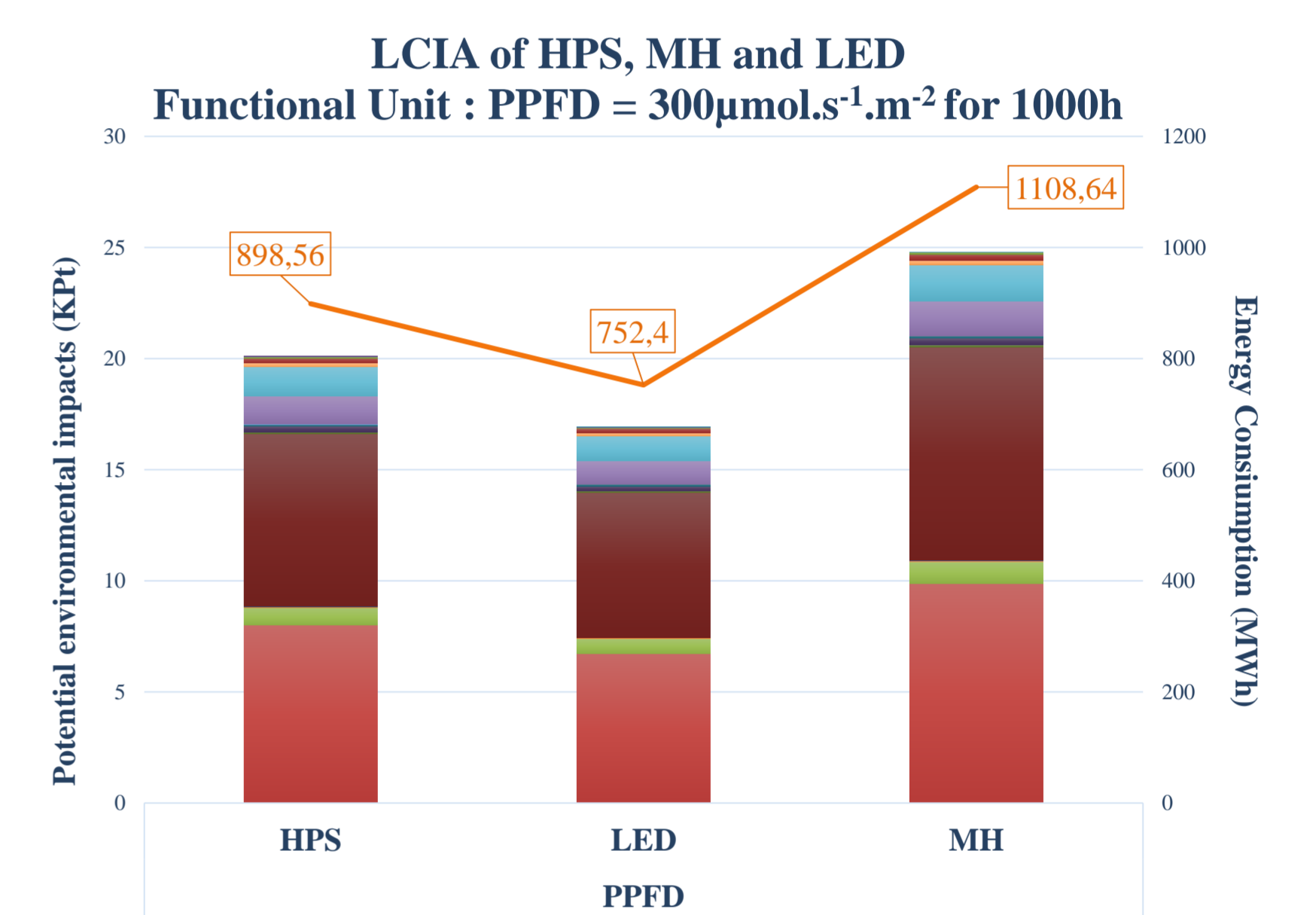


Chart 3 : Potential environmental impacts (KPt) and Energy Consumption (MWh) for HPS, LED and MH lamps providing $300\mu\text{mol}\cdot\text{s}^{-1}\cdot\text{m}^{-2}$ for 1000h.

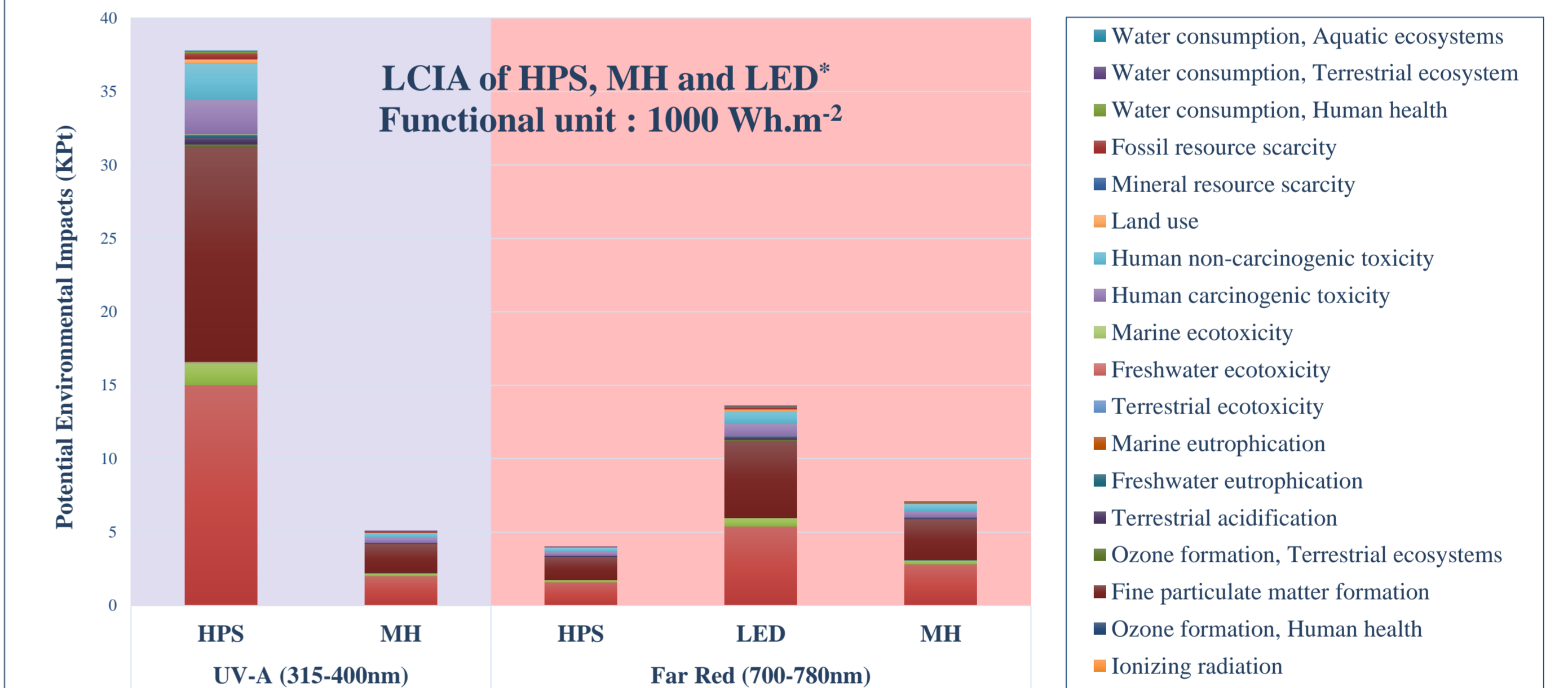


Chart 4 : Potential environmental impacts (KPt) for HPS, LED and MH lamps providing $1000\text{Wh}\cdot\text{m}^{-2}$ over UV-A (315-400nm) and Far Red (700-780nm). *LED lamps do not provide any UV-A

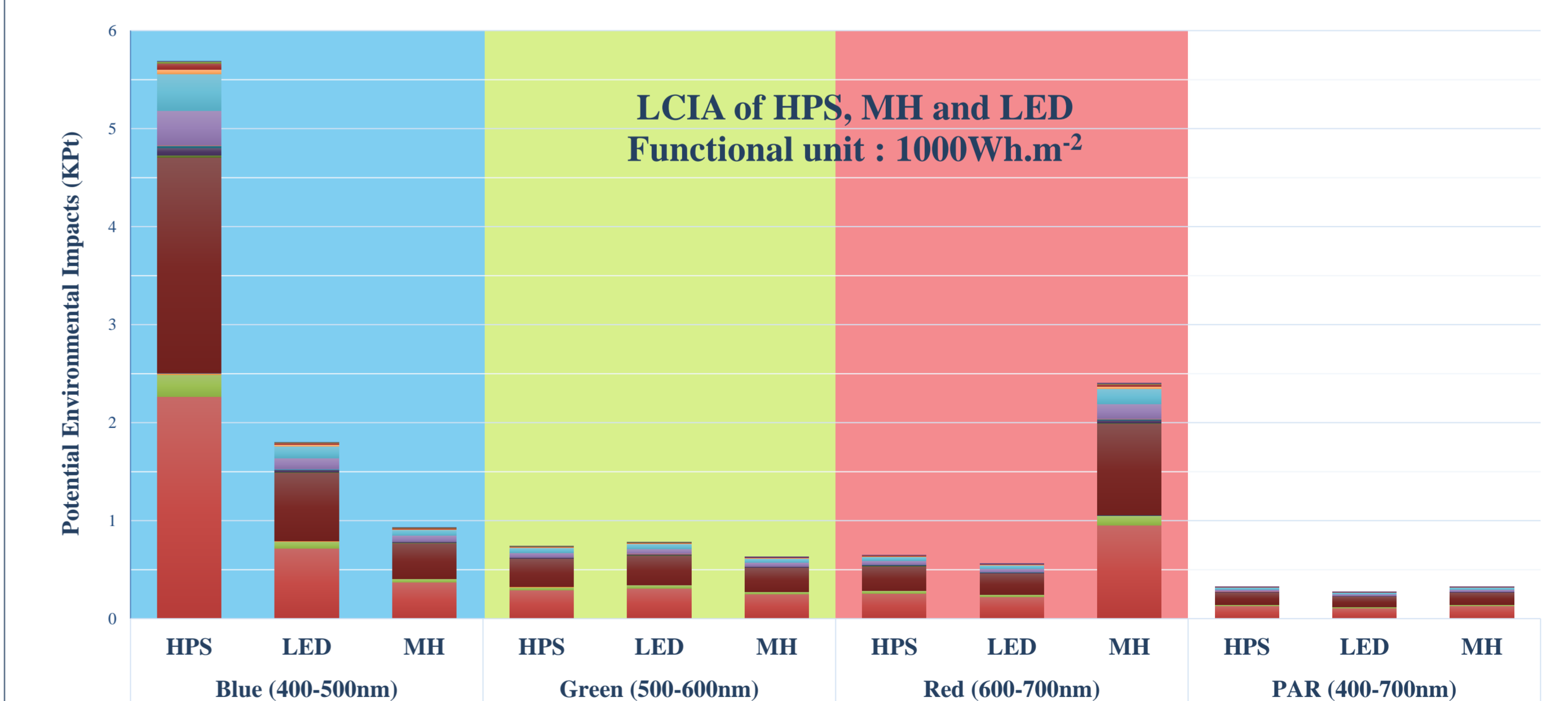


Chart 5 : Potential environmental impacts (KPt) for HPS, LED and MH lamps providing $1000\text{Wh}\cdot\text{m}^{-2}$ over PAR (400-700nm).

Conclusion

- Most of the potential environmental impacts are generated by the energy consumption;
- The carbon intensity of the electrical supply is variable and the impact of energy use may change by up to 20 % depending on use. At present the intensity varies from about 180 to 250 $\text{gCO}_2\text{eq}\cdot\text{kWh}^{-1}$ on a daylight cycle and drops below 100 over the weekend. The trend is to lower carbon intensity but the continued uptake of electric cars may increase the cost and carbon use of night-time electricity, this may impact future impact of this sort of application;
- The higher impact of LED luminaires manufacturing is offset by lower overall power consumption and longer useful life, making the LED configuration the least impactful compared to PAR. However, HPS and MH are still relevant in providing UV-A and Far red which could benefit some crop productions;
- The authors have not attempted a life cycle cost – benefit analysis. Although it would have been straightforward to provide realistic estimates for the relative costs of each lighting design installation it would not have been possible to accurately quantify the benefits in terms of crop production.