HTSM Lighting roadmap

1. Societal challenges and economic relevance

Introduction
Due to the introduction of Solid-State Lighting (SSL) the global electricity usage for lighting is reduced from 19% to 8% today. However, between 2010 and 2050 the demand for electric lighting is expected to triple. Only by embarking in advanced SSL component solutions, intelligent lighting systems based on SSL and using natural daylight as an integral part of these intelligent lighting systems, will we be able to cope with this demand, while stabilizing energy use at its present level.
Next to its impact on energy efficiency, the transition to SSL has enabled much more efficient use of scarce materials (e.g. rare earth in fluorescent). Further research must enable innovative technologies, modular designs, and business models to implement *cradle-to-cradle product chains* in the Lighting industry.
With the advent of the 24/7 economy, human activity is no longer limited to the daytime. By mimicking daylight and (individually) tuning light spectra and distribution to perceptual, psychological, and biological needs, more healthful and effective illumination conditions can be created, *human centric lighting*, which will positively impact people's health, well-being, and performance.
Light can play an important role to fight virus outbreak, reduce bacteria and mold growth.
In the last decades, plant factory (or vertical farm) technology has been introduced for growing vegetables and soft fruits. With a well-controlled environment, new health benefits, food safety, optimized nutrients and increased shelf-life can be offered to consumers. With the progress of light emitting diode (LED) lighting efficiency and the knowledge of light-plant interaction, a better quality control can now be achieved together with improved energy efficiency. Growth strategies combining crop quality attributes (e.g., color, nutrients, shelf life) with efficient growth are key for economic viability of plant factories.
Lighting is increasingly becoming connected, both the Lighting system itself and in connection with other systems in the built environment. Its ubiquitous presence offers the perfect infrastructure for internet access anytime, anywhere. Currently, lighting is becoming an integral part of the Internet of Things (IoT), enabling inclusive, innovative, and reflective societies which will further unlock the added value of *lighting beyond illumination*.

Societal challenges addressed in this roadmap
For each of the following KIAs, "kennis en innovatie agenda's/Knowledge and Innovation plans", the innovations in lighting will contribute:

- KIA Energietransitie en Duurzaamheid / Energy Transition and Sustainability
  Future developments in SSL technology still allow the energy usage of current state-of-the-art LED lighting to be reduced significantly. In a second phase, SMARTification will further drive the energy consumption down by selectively switching off the lighting without compromising the performance.
  To make circular economy for lighting come through new technical interfaces that affordably allow easy maintenance and upgradeability as well as new business models that support circular models need to be developed. In addition, additive manufacturing will help to build circular products by

reusing printing material and reduce transportation by allowing economically affordable local manufacturing.

- KIA Gezondheid en Zorg / Health and Care
  Large-scale migration to cities, increased time spent indoors, and our 24-hour economy have impacted on our light exposure. Such aberrant, unnatural light dark cycles impact on human physiology and functioning and can result in sleep, mood, and circadian rhythm disturbances, in fatigue and cognitive failure, and they even may aggravate certain cancer pathologies. With light for health & wellbeing lives can be improved: e.g. human-centric lighting in indoor environments where people work together, like offices, schools, factories etc, may help prevent or relieve burnout and mood and anxiety related ill-being and disorders; patients recover faster in hospitals and psychiatric care with the right light and health related cost can be reduced; improved light settings at home can help to relax.
  Due to the global Covid-19 pandemic, the interest in disinfection with light has increased significantly. Using UV-C and far-UV viruses in air and on surfaces can be reduced significantly. UV-B can be used to increase the vitamin D levels that has a positive impact on the immune system.
- KIA Landbouw, Water en Voedsel / Agriculture, Water and Food
  With light for Horticulture, animal farming and vertical farming (also known as indoor farming) the quality and quantity of products, health of animals can be improved, as well as the usage of pesticides, water and fertilizers can be decreased. In the case of vertical farming no pesticides are used, and water usage is reduced more than 90 % compared to open field production. This is a strong contribution to a solution for the worldwide food challenge. Vertical farming will also result in local production, shorter food chains, fresher products, higher shelf-life, less waste, and less transport, generating additional environmental benefits.
- KIA Veiligheid / Safety
  In the outdoor space, lighting plays a crucial role to improve road safety and the perception of safety in the street. Using innovations in light spectrum and distribution, these safety aspects can be further enhanced, while safeguarding plant and animal ecology. New optical solutions will reduce light pollution and improve wildlife due to special light that does not disturb certain species. Moreover, lighting can be used for proactive crowd management to enhance safety and security in large scale public environments and events.
  Finally, lighting can be used for communication (Lifi) in high bandwidth and high-security applications which is more cost effective than wired solutions.

World-wide market for this roadmap, now and in 2025

The world-wide market for lighting products, covering both light sources and luminaires, is estimated to grow from USD 115.44 Billion in 2018 to USD 161.58 Billion by 2026, exhibiting a CAGR of 4.4% during this period, https://www.fortunebusinessinsights.com/industry-reports/101542. While LEDs accounted for more than 75% of the turnover of the leading lighting companies in 2019. This transformation quickly followed by the introduction of IoT based, connected, lighting solutions. Consequently, the lighting industry is, after the introduction of LED lighting, again faced with a transformation in its 130 years of existence. Finally, with the introduction of Lifi the lighting industry is also expanding in the multi-Billion communication market.

Competitive position of the NL ecosystem (market and know-how)

The Netherlands has a unique position of strength in the lighting market. The largest global player in lighting is based in the Netherlands, its 2017 turnover equalling 160% of the second and 310% of third global player. Signify (former Philips Lighting) is the world leader in lighting products and services with a market share of around 10% and the only global player in both professional and consumer luminaires. Next to this around 350 SMEs, e.g. lighting designers, installers, distributors and shops, active in the lighting domain are registered with the Dutch Chamber of Commerce, while a substantial knowledge base in solid state technology, optics, embedded software and lighting is found with academia and research institutes, opening access to all competences needed for the future.

By becoming the motor of intelligent lighting, the Dutch lighting eco-system will be able to consolidate its number one position in lighting, both in terms of economic growth and of employment, despite the advent of Asian players that are currently driving the cost roadmap of LEDs and LED retrofit lamps.

Because the Dutch government owns a substantial part of the lighting infrastructure, i.e.: outdoor lighting and public buildings, it is in a perfect position to take the lead in the validation of the R&D results under real life conditions.

2. Applications and technologies

State of the art review (industry and science)

Currently, LEDs are primarily used as replacements of conventional light sources, with a penetration of 15% in the total market. The lighting market will continue to grow with a CAGR of 3% and the LEDification will continue at a rapid pace and reach a level of more than 50% in 2025.

Developments in present and future markets and societal themes

On energy usage, present LED technology has an efficacy around 160 lm/W. The coming years the efficacy will rise above 250 lm/W for current LED technologies and even potentially above 320 lm/W for new LED architectures. To reach these levels, deep understanding of the physical mechanisms behind LED lighting as well as a deep understanding of the perception aspects of multi-coloured LED architectures are needed.

Today, one of the limiting factors in the usage of LED technology embedded in building elements is the size of the driver. Further driver miniaturization is needed. Solutions are to be found in the usage of GaN type of electronic components that allow higher power densities and consequently a smaller size. Commercially, these components start to be available, but the optimized designs still must be found.

Advances in conversion materials are needed to a) allow higher efficacies and b) allow tailored spectra. To reach the high efficacies mentioned above, there is a need for red and green conversion materials with a narrow bandwidth. In addition, there is a strong trend in industry to go to tailored spectra such that the light of a product can be adjusted to the application.

Human-centric lighting is enabled by these new spectra and allows the industry to make light that supports biorhythms, improves concentration, light that is visually more pleasing and has other health effects.

For horticulture applications, it allows tuning of the light (level and spectrum) to the different growth stages of plants, thereby increasing growth efficiency and crop quality. For animals, tuneable lighting can offer improved animal wellbeing in combination with more efficient feed conversion.

For disinfection new applications are possible with the recent advancement in sources and optical components (filters) and other technologies (disinfection robots e.g.).

Both in the consumer and in the professional space connected lighting systems are on the rise and the added value of such IoT systems is ever more appreciated. To create these connected lighting systems that harvest data, the lighting industry needs access to sensor technology that is cost-effective, reliable and application specific while being safe and secure at the same time. In the current industry we see the inroad of micro-wave and thermopile type of sensors. These sensors need dedicated signal processing to extract the data in real-life applications. Artificial intelligence and machine-learning strategies will need to be harnessed to create personalized services, e.g. for healthy light exposure, navigation, and safety purposes. Practical local (edge) data acquisition, processing and management need to be developed such that the real-time requirements of (lighting) applications can be satisfied, as well as the security and privacy requirements.

Questions and milestones for this roadmap in 2025

It is proposed that advancement of the state-of-the art in lighting technology will be approached from four different angles, representing the sub-eco-systems of lighting in the Netherlands:

A. Breakthroughs in basic LED and light conversion technology: excellence in science
   a. New SSL source architectures (micro- and nano-LED, UV, laser sources)
   b. New conversion technologies, materials, and basic understanding of the scattering behaviour of these materials
   c. Spectral engineered solutions to address new markets like Human-Centric Lighting, horticulture etc. and the validation thereof.
   d. Reliability models and degradation mechanisms of the sources and full systems

B. Innovation at the product level: leveraging the new opportunities that the recent advent of SSL devices has provided for lighting products (opportunity driven technology push). Challenges that we foresee here are:
   a. Smaller LED solutions, miniaturized driving solutions for unobtrusive solutions, based on e.g. IC integration and GaN components.
   b. Integrated optical, thermal solutions allowing function integration and long-lifetime solutions
   c. New tools for the design of LED products (optical, thermal, mechanical, system design tools), including digital twin technology. For optical e.g. free shape inverse design strategies, scattering modelling, fast and accurate simulation tools and imaging optics design strategies are needed to come with new innovative solutions.
   d. Hard- and software reliability to allow upgradable, reliable solutions and to safeguard all user requirements on complex lighting systems.
   e. New (additive) manufacturing technologies deployed to LED products to allow for freeform (2D, 3D) luminaire manufacturing. This allows for building circular products and reduce transportation by allowing local manufacturing
   f. New applications and segment specific solutions based on spectral tuning (horticulture, light for farming, human centric lighting applications etc).
   g. Underpinning the application, safety, and effectiveness of different wavelength regimes (405nm, UV-B, UV-C, far UV) in relation to disinfection. Furthermore, we need optical components for these wavelengths and solve the related material degradation challenges.

h. The impact of certain wavelength (e.g. UV-B) on hormone levels (e.g. the vitamin D) and relation to the health and effectiveness of the immune system needs further research.

C. Innovation at the lighting system level: Connected lighting infrastructure provides intelligent lighting but is also an omnipresent network that can connect various verticals facilitating (IoT) services beyond lighting. Challenges that we foresee are:

a. Dealing with complexity: Lighting systems should remain easy to setup, use, and manage. Generic reusable architectural patterns and lighting system architectures for interoperability with legacy systems are needed.
b. Signal processing: deriving low-level features from raw (sensor) signals for presence detection, people counting, context detection, emotion detection etc.; building digital twins.
c. Intelligent algorithms and data analysis: translating sensor data into insights with minimal device resources while preserving privacy or confidentiality. Data analysis supporting lighting services and services beyond lighting, aligning the lighting roadmap with the ICT roadmap.
d. User interaction: balance between manual versus (context-aware) automated control, personalized versus group control, user interface development, end-user programming.
e. Wireless lighting networks: reliable and fast unicast, broadcast and multicast, especially in (radio) duty-cycled networks without sacrificing energy efficiency; improved performance of optical wireless communication over LED and laser light sources.
f. System-of-systems integration: lighting system integration with other ambient intelligence systems, such as building management and home automation, video surveillance, smart grids or traffic management systems.

Creating added value beyond illumination: Next to the image forming effect of light via the eye, the is also a non-image forming effect. Non-image forming effects have been established as crucially important for mental and physical health. Yet much more insight is needed, before these can be implemented in intelligent, personalized, and/or human-centric systems and services. But also new challenges in visual, image forming aspects of light have arisen: visual performance, visual comfort and light sensitivity have gained in relevance with the introduction and large-scale implementation of new light sources and requirements of high light levels for non-image forming effects (circadian entrainment, alerting and vitalizing effects).

In horticulture and lighting, concepts for design and control of a vertical farm that allows guarantees on quantity and quality of production of fresh vegetables every day of the year, completely independent of weather, climate change, or location on earth (urban versus rural area, arctic versus tropical climates). Taste, aroma, appearance, shelf life, and nutritional value should be substantially improved (>20% improvement of the most relevant quality parameters), while there is no pesticide use, no nutrient emission, only 2-4 litres water used per kg product, at least twentyfold less land usage, and less energy usage than greenhouse production per unit product. Light is essential to produce food and essential for the quality of the crop. Achieving a successful production of vegetables from a vertical farm cannot be achieved without a smart way of using light.

Challenges that we foresee:

a. Optimization of timing, dosage, and spectral tuning for circadian and acute effects of light; Establishing the size of effects, requirements for both curative (therapeutic) and preventive physical and mental health applications.
b. Translation of insights to concrete and actionable mathematical models of light effects: validation of circadian models for realistic exposure patterns; development models for acute light effects; inclusion of spectral composition in these models
c. Comfort and adaptation: understanding the role of melanopsin, of dynamic, coloured, and/or non-uniform light conditions, of coherence of light in the case of lasers, and of interpersonal differences in visual performance, comfort, and light sensitivity
d. Impact of the aesthetics and dynamics of light to image forming and non-image forming effects in reducing the prevalence of mood, stress, and anxiety related ill-being and disorders
e. Optimizing the balance between electric light and daylight from a sustainability perspective, but also in view of human health and mental wellbeing
f. Balancing safety needs with energy and sustainability targets, and thoughtful, sensible, and effective strategies for crowd nudging and management.
g. Find and optimize lighting characteristics (intensity, light sum, spectrum, schedule) for each crop grown without compromising quality and yield.
h. Interaction of light with environmental factors as measured by sensors to give feedback on predicted production and improve yield while growing by means of data analytics and data modelling.

3. Priorities and implementation

Implementation of this roadmap in public-private partnerships and ecosystems

In the recent years, fruitful collaborations in the Dutch lighting innovation eco-system were initiated, resulting in many collaborations established in public-private partnership projects like (not exhaustive): MSCA ITN ETN LightCap, NWO TTW Perspectief Freeshape Scattering Optics, TKI HTSM Phase space ray tracing, TKI Intellight/Intellight+, OpenAIS (Photonics PPP – H2020) CSSL, EnLight, GreenElec, OPERA (all ENIAC), Hertz, SEEL (all CATRENE), ISLES 2014 (Point-One), Aeviom, Fast2Light, Place-IT, Flex-o-Fab, MMP, Terasel, SSL-erate, Clean4Yield, IMOLA (all FP7), DIMAP, PhotoLED (H2020), Demanes, DEWI (ARTEMIS), IoSense, SCOTT, DELPHI4LED (ECSEL), PS-CRIMSON (ITEA3) and a FOM_IPP on "Improved Solid State Light Sources". Additionally, the H2020 / KIC / EIT Digital projects BrightAgeing, "Elevators & Lighting", ALIGRE and LumiPark explored the requirements for market introduction of connected lighting applications.

The EUREKA programmes ITEA3 and PENTA, as well as the ECSEL JU – most relevant to HTSM – have experienced prominent Dutch participation in the recent past. Hence, the Dutch lighting eco-system wants to continue this extensive collaboration, also with the European players in the lighting field that are established through these projects, with a continuous involvement of the Dutch SMEs, widening the scope to also include systems and services.

Details of the roadmap are reflected in the multi-year program: Light and Intelligent Lighting.

Linkage with other innovation instruments (e.g., public purchasing and risk investment)

Currently, LEDs are rapidly entering the market as replacement for less efficient conventional (e.g. incandescent or fluorescent) lamps (either as retrofit lamps or as new modules). The potential of digital and connected lighting has recently started to be addressed, think of the extremely successful Philips HUE proposition (connected lighting for the consumer space).
The public authorities, owning a substantial fraction of the existing indoor and outdoor lighting infrastructure, can speed up the uptake of digital lighting in the Dutch market as a launching customer and through innovative purchasing. The public authorities will benefit from the additional savings offered by combining LED technology with controls, while the industry will be able to optimize his offer much faster based on the feedback obtained from the launching customer. An example of such a project is `Jouw licht op 040`.

Collaboration in and leverage with European and multi-national policies and programs

This roadmap is closely linked with the European roadmap put together by the Photonics21 European Technology Platform in close cooperation with Lighting Europe. Signify the work group dealing with "Advanced Lighting, Electronics and Displays". People from TNO, Holst Centre and Signify were deeply involved in editing of the latter roadmap in collaboration with the relevant European players from academia, research industry, start-ups, SMEs and large industry. Through this Photonics21 innovation roadmap we do align with the Photonics PPP work programmes in Horizon 2020, and by mobilizing the lighting eco-system it enables us to contribute substantially to several of the Key Enabling Technologies (KET).

4. Partners and process

Partners in this roadmap from industry, science, departments, regions and cities

In previous versions, the following partners have been involved in the definition of this roadmap:

Academia	RUG, TU/e, TUD, UT, UU, , WUR
Institutes	NWO-i AMOLF, TNO-ESI, Holst Centre, ILI, TNO, M2i, MESA+, TNO energy transition, , TNO industry, TNO buildings, infrastructure & maritime, TNO circular economy & environment, TNO , TNO Healthy Living, TNO Traffic & transport, TNO Information & communication Technology, VSL, Waag Society, Dekra, Dutch Polymer Institute, PhotonDelta
Industry	Signify, Studio Philip Ross, Studio Tom, VDL etg, Consem, , U'll learn & Like IT bv., MOBA, ENGIE, Philips, LEAP bv, Key2China, EUR, Fujifilm Manufacturing Europe BV, Cooperative smart sustainable farming, Sparckel – life needs light, CSSF, SLD Laser, UNA, SC, High Tech NL

Process followed in creating and maintaining this roadmap (with role of SME)

Signify (being a global market leader in lighting solutions) has led the process to come to this updated HTSM Lighting roadmap document for the Netherlands in close cooperation with High Tech NL and the Intelligent Lighting Institute of TU/e. It reflects input gathered from various sources and includes inspiration from contacts with universities and knowledge institutes as well as industry.
On 21 November 2019, a workshop event with three parallel session and participants of different stakeholders was held at the campus of TU/e in Eindhoven as part of the outreach event of the Intelligent Lighting Institute. The different reach lines of the ILI have presented their running research

activities and have shared their vision on trends and new directions relevant the Lighting research and industry in the Netherlands. The participants contributed with new ideas in the three-parallel session by brainstorming. This event was well attended by nearly 60 interested parties. The discussions in this workshop have been used as input material for this roadmap.

5. Investments [1]

Roadmap	**2020**	**2021**	**2022**	**2023**
Industry	4,1	4,9	5,3	4,8
TNO	0,6	0,7	0,8	0,7
NLR	0,0	0,0	0,0	0,0
NWO	2,0	2,4	2,6	2,4
Universities	0,5	0,6	0,7	0,6
Departments and regions (excluding TKI)	1,0	1,2	1,3	1,2
Grand total	8,2	9,8	10,8	9,7

European programs within roadmap	**2020**	**2021**	**2022**	**2023**
Industry	2,6	3,1	3,4	3,0
TNO	0,1	0,1	0,1	0,1
NLR	0,0	0,0	0,0	0,0
Now	0,0	0,0	0,0	0,0
Universities	0,0	0,0	0,0	0,0
EZK co-financing of European programs	0,0	0,0	0,0	0,0
European Commission co-financing	3,9	4,6	5,1	4,6
Grand total	6,5	7,8	8,6	7,7

[1] R&D in public-private partnership, including contract research; all figures in million euro cash flow per year (cash plus in-kind contribution)