Energy Efficiency Technology Roadmap

Volume 3: Lighting

March 2016

Enhanced PDF Functionality

Functionality of the PDF version of this document has been enhanced in the following ways:

- **Bookmarks:** Enabled PDF reader applications (i.e., Adobe Acrobat) can navigate this document using the Bookmark feature.
- **Embedded Links:** The Table of Contents has been linked to the appropriate sections of the document.
- **"Back to Table of Contents":** In the footer of each evenly-numbered page is an embedded hyperlink back to the Table of Contents.
- **Control + F:** As always, one can navigate through the document by searching for specific words or phrases by pressing the "Control" and "F" keys simultaneously.

Special Note

This document is one component of the Energy Efficiency Technology Roadmap (EE Roadmap), published by the Bonneville Power Administration (BPA) on behalf of regional stakeholders. This current version has been updated with input from key Agency subject matter experts in late 2015. These updates include:

- Inclusion of new content within the "Commercial Sector: Advanced Controls" roadmap.
- Extensive revisions to the "General Lighting," "Solid State Lighting," "Lighting Controls," "Luminaires," and "Daylighting" roadmaps.

For the background and purpose of the full EE Roadmap, a complete list of the project team and contributors, and other explanatory and complementary information, see Volume 1: Introduction & Background.

While BPA has funded and managed the overall development and maturation of this Energy Efficiency Technology Roadmap since 2009, the effort would not have been possible without the active engagement of a diverse array of subject matter experts from organizations and institutions throughout North America. Since the beginning of this roadmapping project, more than 200 participants representing 119 organizations have contributed approximately 5,120 hours and $1,100,000 worth of voluntary input. Their expertise is essential to this project. See Volume 1 for a complete list of contributors.

There is still much collaborative work to be done to improve our understanding of the current energy efficiency technology research landscape but we are making strides in the right direction and we truly appreciate the dedication and contributions of all who have been a part of this important endeavor.

For more information about the Energy Efficiency Technology Roadmap, contact:

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Using the Roadmap

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Introduction to this Volume

This volume has been significantly updated since the previous version (March 2015), including:

- Removal of the “Task / Ambient Lighting” section. For optimal performance, this area first requires major advances in lighting controls. After lighting controls work well, then effective task / ambient / vertical lighting can be developed. The prospect for this is so remote, and major market forces are moving so fast, that the probability of direct benefit to BPA and regional stakeholders is extremely low.
- Addition of the “Commercial Sector: Advanced Controls” section based on input from subject matter experts highlighting opportunities to target utility R&D funds for specific technology characteristics of strategic regional importance and significant energy savings benefits.
- Content updates for the remaining roadmap diagrams.

This volume contains roadmaps in these residential and commercial sector Technology Areas:

- General Lighting
- Solid State Lighting
- Lighting Controls
- Luminaires
- Daylighting
- Commercial Sector: Advanced Controls

Technology Area Definitions

General Lighting

Technologies and strategies to optimize the use of lighting fixtures, components, and controls for general illumination (rather than decorative, traffic, signs, etc.).

Solid State Lighting

More affordable, efficacious, and reliable light emitting diode (LED) lighting system, using technologies and techniques that take full advantage of LED’s characteristics, such as directionality, long life, and controllability while mitigating concerns such as heat management, lumen maintenance, color-shift, and component failure.

Lighting Controls

Technologies and design approaches to improve the effectiveness and usability of lighting controls to minimize energy use while maintaining good lighting quality.

Luminaires

Materials and designs to improve the optical efficiency of luminaires, which may consist of a body, ballasts, reflector, and lens.

Daylighting

Technologies and strategies to maximize the use of daylight and minimize the need for electric lighting while maintaining good quality lighting that promotes health and productivity.

Commercial Sector: Advanced Controls

Specifically for the Commercial Sector, technologies and design approaches to improve the effectiveness and usability of lighting controls to minimize energy use while maintaining good lighting quality.

Other Sources

The list below is intended to be broadly representative rather than exhaustive and will be updated as new information becomes available.

U.S. Department of Energy Office of Energy Efficiency and Renewable Energy, *Solid-State Lighting Research and Development: Multi-Year Program Plan*, prepared by Bardsley Consulting (and others), April 2012, http://apps1.eere.energy.gov/buildings/publications/pdfs/ssl/ssl_mypp2012_web.pdf.

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Using the Roadmap

The EE Roadmap is a reference tool designed to be a living, working document. It was not crafted with any expectation that it would be read from beginning to end like a traditional report or narrative. Rather, its design allows for quick reference to technology development research agendas in relation to energy efficiency product and service areas in the residential, commercial, and industrial sectors.

Roadmap content is organized into eight volumes. Volume 1 provides an overall introduction and background, defines key terms and concepts, and guides readers in understanding how roadmap content is organized and interpreted. The remaining volumes contain multiple roadmaps within the respective area:

- Volume 1: Introduction & Background
- Volume 2: Building Design/Envelope
- Volume 3: Lighting
- Volume 4: Electronics
- Volume 5: Heating, Ventilation, and Air Conditioning
- Volume 6: Sensors, Meters, and Energy Management Systems
- Volume 7: Industrial Food Processing
- Volume 8: Combined Heat & Power

In addition to these volumes, there are two ancillary documents to the EE Roadmap:

- Appendix A contains process documents for all of the technology roadmapping workshops held to date, including minutes from each workshop.
- Appendix B contains more information, when available, about existing R&D programs identified in roadmap diagrams.

Disclaimer

Some roadmaps, project summaries, and appendix pages identify specific vendors, commercial products, or proprietary systems and technologies. BPA, its partner institutions, and other stakeholders make these references solely for context; these references do not constitute endorsement on the part of BPA, the Department of Energy, or any stakeholder involved in the creation and refinement of these roadmaps.

Roadmap "Swim Lane" Definitions

Roadmap diagrams are composed of the following four "swim lanes":

Drivers: Critical factors that constrain, enable, or otherwise influence organizational decisions, operations, and strategic plans. These factors can include: existing or pending regulations and standards; the environment; market conditions and projections; consumer behavior and preference; and organizational goals and culture, among others.

Capability Gaps: Barriers or shortcomings that stand in the way of meeting drivers.

Technology Characteristics: Specific technical attributes of a product or service necessary to overcome capability gaps.

R&D Programs: The iterative process undertaken at universities, national laboratories, some businesses, and related organizations to generate new ideas for products and services, develop models and prototypes, evaluate these in laboratory settings, and conduct engineering and production analyses with the goal of delivering the product or service to the marketplace. Within the *Roadmap Portfolio* the generic abbreviation "R&D" is to be understood as including, when appropriate, design, deployment, and demonstration in addition to research and development.

What is the difference between a "Technology Characteristic" and a "Capability Gap?"

A food processing company finds that the machine it currently uses to peel potatoes removes a significant amount of the flesh of the potato. Removing too much of the flesh reduces the yield of each processed potato and this reduced yield means that the company is not getting as much saleable product out of each unit of potatoes. The company must also pay increased costs to dispose of their wastes.

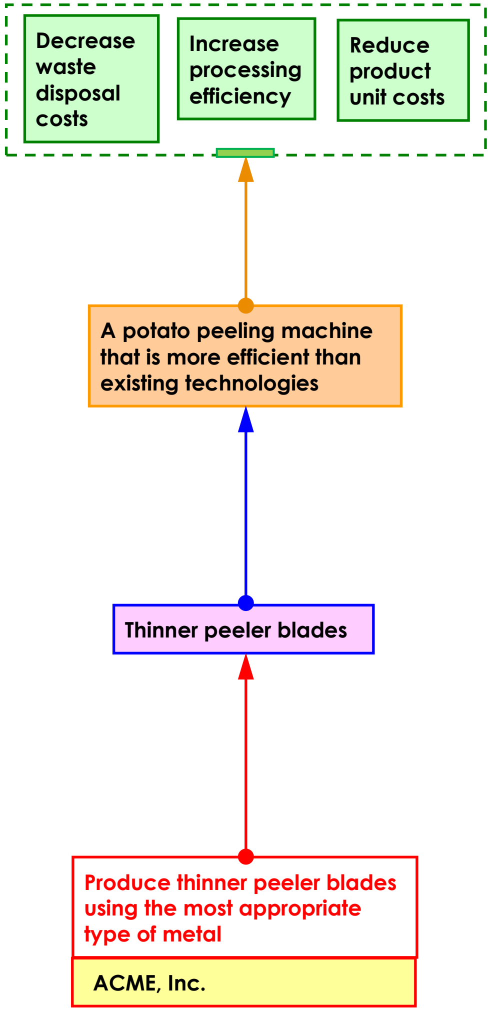
Faced with this situation, the company is facing three Drivers: 1) the desire to increase processing efficiency; 2) the desire to reduce product unit costs; and 3) the desire to reduce waste disposal costs.

Motivated by these drivers, company officials are seeking a solution that will improve the yield of their potato peeling machine. This is their Capability Gap: A peeling machine that is more efficient than existing technology.

Company officials take their request to their engineering team and ask them to develop a solution that will overcome the capability gap and, thereby, meet the three drivers. The engineering team applies their technical expertise to suggest that if they were to reduce the thickness of the peeler cutting blade they would be able to meet the requirements and overcome the capability gap. Thus the engineers have established a Technology Characteristic.

The engineers' next step is to commence an R&D Program in which they investigate the kinds of metal they could use to create thinner blades and then test these blades.

The diagram to the right illustrates this example:



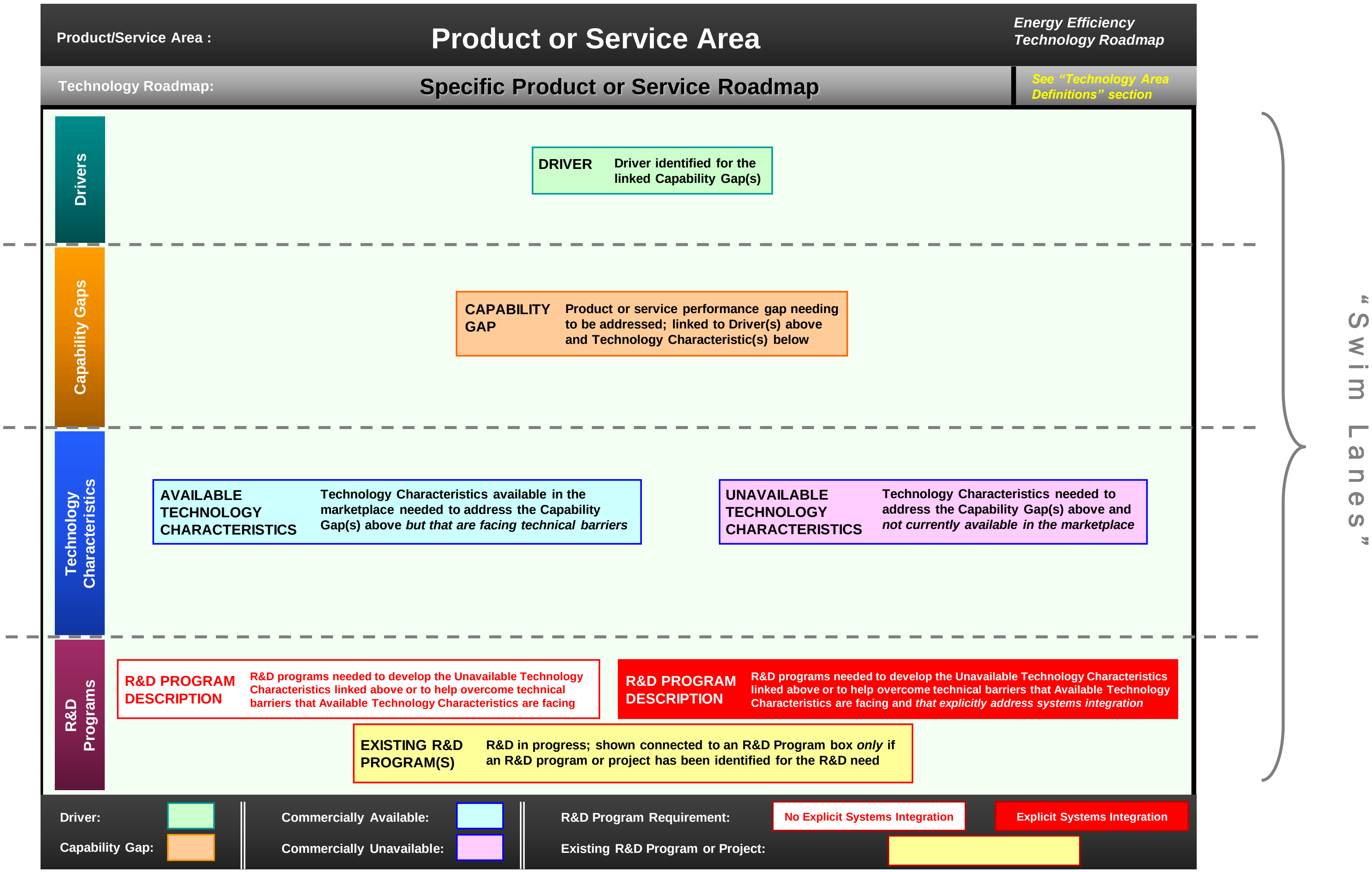
Drivers:
What are the reasons to change?

Capability Gaps:
What are the barriers to change?

Technology Characteristics:
What are the technological solutions needed to overcome barriers to change?

R&D Programs:
What are the research programs and key research questions to pursue to develop technological solutions?

Roadmap Diagram Key



R&D Program Summaries Key

R&D Program Title. Brief summary of R&D program needed to develop the associated Unavailable Technology Characteristics or to help overcome technical barriers that Available Technology Characteristics are facing.

Existing research: Institution(s) listed where R&D program(s) are ongoing.

- Brief descriptive summaries of each institution's R&D program that may include, where applicable, hyperlinks to web pages and/or reference to further program details in Appendix B of the *National Energy Efficiency Technology Roadmap Portfolio*.

Key research questions:

1. One or more research questions that subject matter experts have identified as among the key questions and topic areas to pursue within the R&D program or project; numbers provided for identification only and do not imply prioritization.

R&D Program Title. Brief summary of R&D program needed to develop the associated Unavailable Technology Characteristics or to help overcome technical barriers that Available Technology Characteristics are facing.

Existing research: None identified. *[R&D program titles that do not have an associated yellow box indicating "Existing R&D Program or Project," by definition, are not underway.]*

Key research questions:

1. One or more research questions that subject matter experts have identified as among the key questions and topic areas to pursue within the R&D program or project; numbers provided for identification only and do not imply prioritization.

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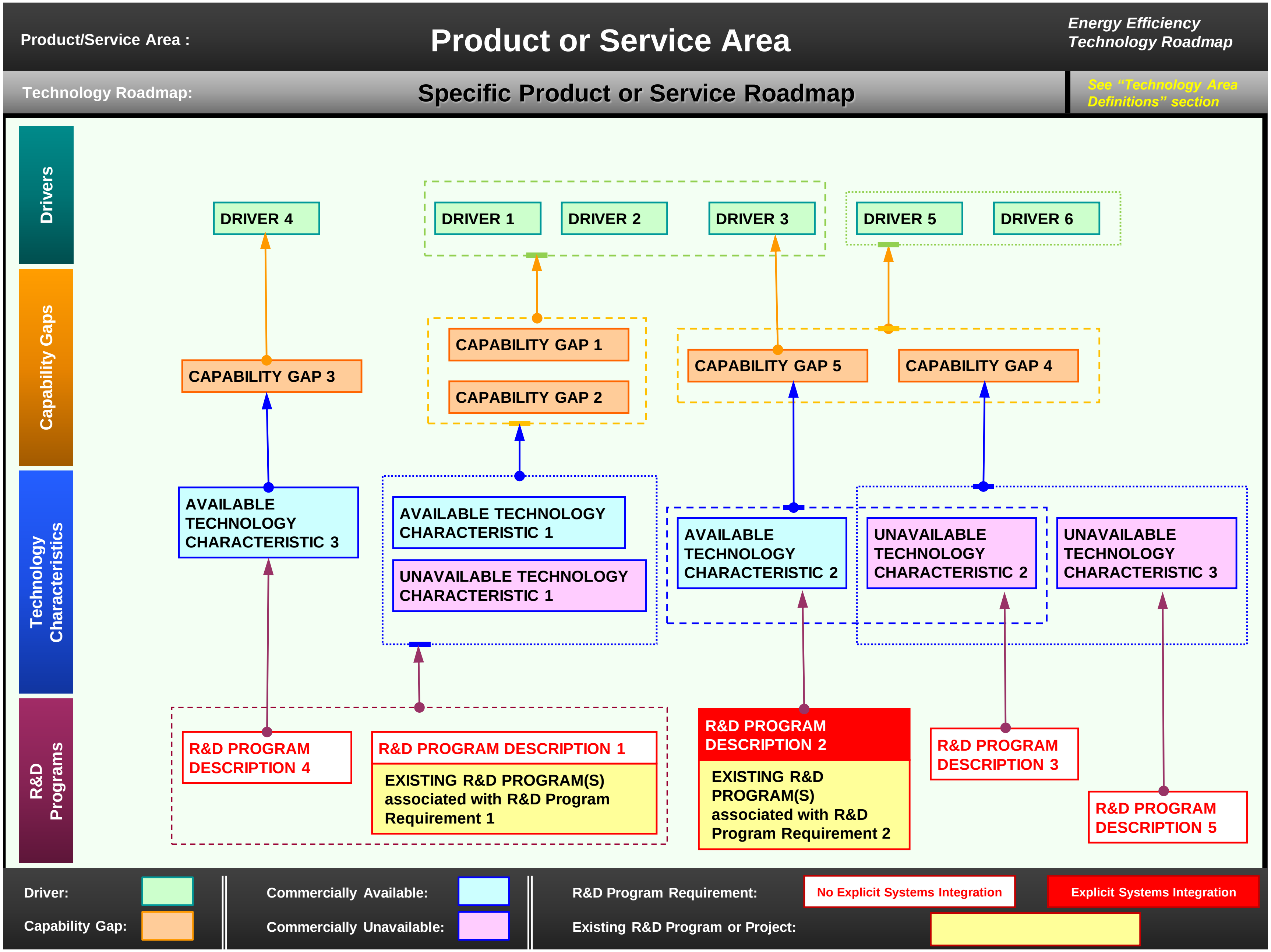
How to Interpret Roadmap Pages



The diagram above represents a typical EE Roadmap page. The most straightforward way to interpret portfolio pages is from the R&D Programs "swim lane" at the bottom up through the Technology Characteristics, Capability Gaps, and Drivers swim lanes.

	Arrows connect individual or groups of boxes in swim lanes to identify critical connections between them.
	Dotted and dashed lines indicate that two or more elements in a swim lane are associated and linked either to another element (or group of elements) in the swim lane above and/or below.
	Short, thick solid lines indicate that the arrow is connecting to the dotted or dashed line surrounding two or more boxes.

Thus, in the diagram on the preceding page, the red arrow connects R&D Program Description 4 (at bottom left) to Available Technology Characteristic 3; the blue arrow connects Available Technology Characteristic 3 to Capability Gap 3; and the orange arrow connects Capability Gap 3 to Driver 4. This means that R&D Program Description 4 helps meet Driver 4. Expressed in another way, meeting the requirements of Driver 4 is a rationale for engaging in R&D Program Description 4.

For purposes of illustration some of the other associations to be drawn from the diagram above are explained below. The following abbreviations are used in the examples:

- R&D = R&D Program Description
- ATC = Available Technology Characteristic
- UTC = Unavailable Technology Characteristic
- CG = Capability Gap
- D = Driver

R&D 1 and R&D 4 linked to D 1, D 2, and D 3

R&D 1 and R&D 4 are associated by the surrounding dashed box because they both contribute directly to UTC 1 and ATC 1. This is shown by the red arrow from R&D 1 and R&D 4 to the dotted blue box surrounding UTC 1 and ATC 1.

Both of these technology characteristics, in turn, are associated with CG 1 and CG 2, and both of these capability gaps are linked to D 1, D 2, and D 3.

R&D 3 linked to D 3, D 5, and D 6

R&D 3 is linked to UTC 2, as the red arrow indicates, but *not* to ATC 2 or UTC 3 because the red arrow links directly to the UTC 2 box and not the blue dashed or dotted lines.

UTC 2 is linked to both CG 4 and CG 5 in the following ways: first, the blue dotted box associates both UTC 2 and UTC 3 and these together are linked to CG 4 by a blue arrow; next, the blue dashed box associates both UTC 2 and ATC 2 and these are linked by a blue arrow to CG 5.

CG 4 and CG 5 are associated with one another as indicated by the dashed orange box surrounding them and an orange arrow links both capability gaps to D 5 and D 6.

Though CG 4 and CG 5 are associated in their linkage to D 5 and D 6, CG 5 independently is linked to D 3, as the orange arrow connecting CG 5 and D 3 indicates.

R&D 2 linked to D 3

A red arrow links R&D 2 with ATC 2. R&D 2 is identified with a red-filled box, denoting that this research addresses a need for an integrated systems approach.

ATC 2 and UTC 2 are associated as is shown by the blue dashed box surrounding them. The blue arrow from this box connects to CG 5.

An orange arrow links CG 5 to D 3 but *not* to D 1 and D 2. These three drivers are associated with one another but only in terms of their linkage to CG 1 and CG 2, not in terms of their linkage to CG 5.

Product/Service Area : **LIGHTING**

Energy Efficiency Technology Roadmap

Technology Roadmap: **General Lighting (1 of 2)**

See "Technology Area Definitions" section

Drivers

- Professional design and more accurate modeling tools are now available to allow better and more efficient lighting designs
- Lighting retrofits happen for many reasons which may or may not include using optics designed for the new light source. The challenge is to make it easier to improve the lighting quality and efficiency during a retrofit
- Lighting should contribute to the health and productivity of occupants
- General lighting should provide occupant comfort and satisfaction
- The use of constantly evolving computer systems, along with changing work staff and their preferences, make a highly flexible and controllable lighting system in the workspace desirable

Capability Gaps

- Need for better, cheaper software to model and help people visualize a new lighting design
- Existing professional design and modeling tools inadequately deal with new lighting technology and do not include all necessary characteristics
- Need to develop tools that help designers and contractors optimize use of solid state lighting (SSL) technologies by application, and design luminaire layout

Technology Characteristics

- Understanding characteristics of new technologies
- A recognized visual acuity metrics which accounts for eye response characteristics with regards to spectrum and light level (exterior, further than current Illuminating Engineering Society of North America (IESNA))

R&D Programs

- Lighting product evaluation — LRC NLPIP
- Unified lighting standard and measurement — LRC

Driver: | Capability Gap: | Commercially Available: | Commercially Unavailable: | R&D Program Requirement: No Explicit Systems Integration / Explicit Systems Integration | Existing R&D Program or Project:

R&D Program Summaries

Unified lighting standard and measurement. Explore a more intricate visual acuity standard and its measurement.

Existing research: Rensselaer Polytechnic Institute Lighting Research Center (LRC).

- LRC visual performance research: http://www.lrc.rpi.edu/programs/nlpip/lightinganswers/fullspectrum/claims.asp.
- LRC unified system of photometry: http://www.lrc.rpi.edu/resources/newsroom/pdf/2006/ImplementUnifiedSystemProject.pdf.
- LRC Universal Lumens: see https://conduitnw.org/Pages/File.aspx?RID=3066.

Key research questions:

1. Can an inexpensive easy to use tool be developed that offers contractors / designers / auditors the ability to measure the correct characteristics for visual acuity (photopic, mesopic, scotopic, correlated color temperature (CCT), color rendering index (CRI))?
2. Can existing research be synthesized to create a user friendly, unified standard for lighting?
3. Can a tool be created to display visual acuity performance and expected benefit?

Lighting product evaluation. Evaluate characteristics of new lighting technologies and disseminate result to lighting specifiers.

Existing research: Rensselaer Polytechnic Institute Lighting Research Center (LRC) National Lighting Product Information Program(NLPIP).

- LRC NLPIP: http://www.lrc.rpi.edu/programs/NLPIP/index.asp.
- *[Summaries of existing research pending]*

Key research questions:

1. What are photometric and dimming characterizations of light-emitting diode (LED) MRIGS? *[Note: Unsure if "MRIGS" is the correct transcription of data provided by subject matter experts and, if so, what "MRIGS" means.]*

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Product/Service Area :

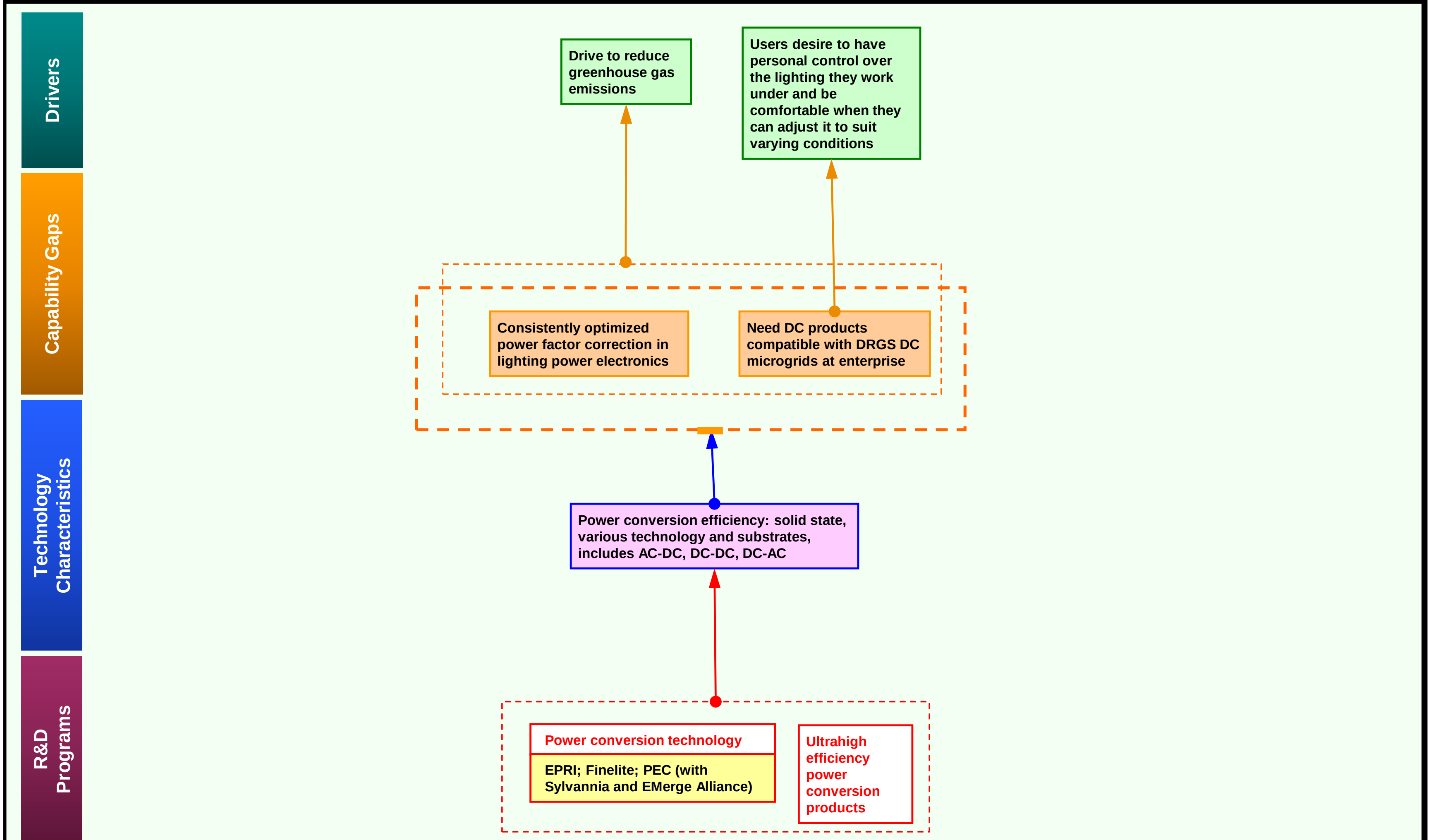
LIGHTING

Energy Efficiency Technology Roadmap

Technology Roadmap:

General Lighting (2 of 2)

See "Technology Area Definitions" section



Driver: | Capability Gap: | Commercially Available: | Commercially Unavailable: | R&D Program Requirement: No Explicit Systems Integration / Explicit Systems Integration | Existing R&D Program or Project:

R&D Program Summaries

Power conversion technology. (Summary not yet provided.)

Existing research: EPRI; Finelite; Pacific Energy Center (PEC) forthcoming withSylvannia and Emerge Alliance.

- Pacific Energy Center (PEC): http://www.pge.com/pec/.
- *[Summaries of existing research pending]*

Key research questions:

1. What substrates are best?
2. What semiconductor technology best performance voltage range?
3. How to accelerate deployment basic research into applications?

Ultrahigh efficiency power conversion products. (Summary not yet provided.)

Existing research: None identified.

Key research questions:

1. Which technology can achieve switching frequencies on the order of 10-20 MHZ?
2. Can function be incorporated into integrated circuits (ICs) (switching devices control, etc)?
3. Can efficiency of 97%+ be achieved?
4. Can a firm factor [form factor?] reduction of 2X or more be achieved?
5. Products should include AC-DC, DC-DC, and DC-AC conversion.

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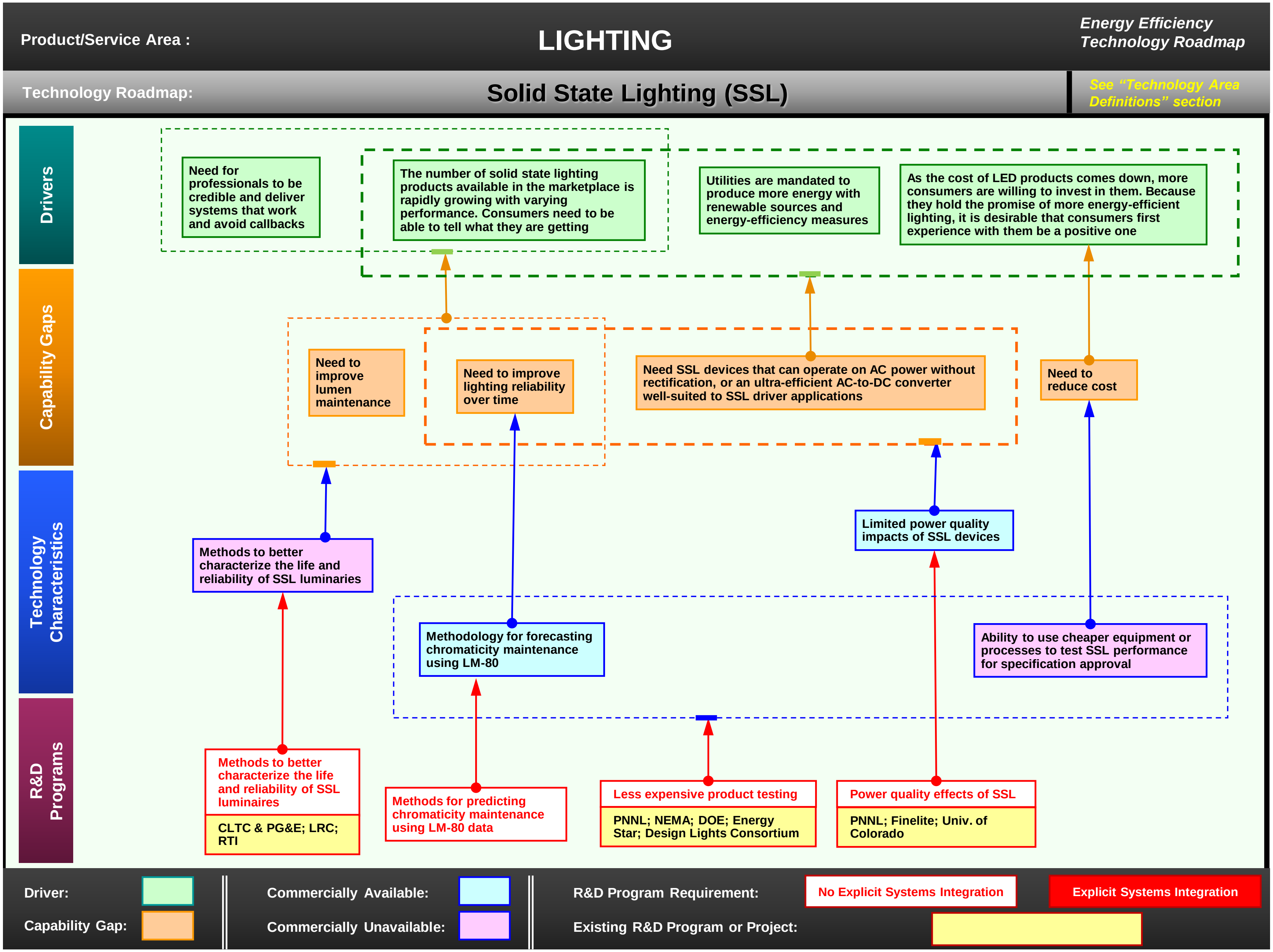


Product/Service Area :
LIGHTING
Energy Efficiency Technology Roadmap
Technology Roadmap:
Solid State Lighting (SSL)
See "Technology Area Definitions" section
Drivers
Capability Gaps
Technology Characteristics
R&D Programs
Need for professionals to be credible and deliver systems that work and avoid callbacks
The number of solid state lighting products available in the marketplace is rapidly growing with varying performance. Consumers need to be able to tell what they are getting
Utilities are mandated to produce more energy with renewable sources and energy-efficiency measures
As the cost of LED products comes down, more consumers are willing to invest in them. Because they hold the promise of more energy-efficient lighting, it is desirable that consumers first experience with them be a positive one
Need to improve lumen maintenance
Need to improve lighting reliability over time
Need SSL devices that can operate on AC power without rectification, or an ultra-efficient AC-to-DC converter well-suited to SSL driver applications
Need to reduce cost
Methods to better characterize the life and reliability of SSL luminaires
Limited power quality impacts of SSL devices
Methodology for forecasting chromaticity maintenance using LM-80
Ability to use cheaper equipment or processes to test SSL performance for specification approval
Methods to better characterize the life and reliability of SSL luminaires
CLTC & PG&E; LRC; RTI
Methods for predicting chromaticity maintenance using LM-80 data
Less expensive product testing
PNNL; NEMA; DOE; Energy Star; Design Lights Consortium
Power quality effects of SSL
PNNL; Finelite; Univ. of Colorado
Driver:
Capability Gap:
Commercially Available:
Commercially Unavailable:
R&D Program Requirement:
No Explicit Systems Integration
Explicit Systems Integration
Existing R&D Program or Project:

R&D Program Summaries

Methods to better characterize the life and reliability of SSL luminaires. There are no consensus methods for characterizing the life and reliability of SSL luminaires. Many manufactures presently use L70 lamp maintenance as surrogate for life. This is an improper characterization. Better methods are needed.

Existing research: University of California Davis California Lighting Technology Center (CLTC) / Pacific Gas & Electric; Rensselaer Polytechnic Institute Lighting Research Center; Research Triangle Instiute.

- *[Summaries of existing research pending]*

Key research questions:

1. Is it possible to develop a unified metric that captures lumen maintenance and all other major failure modes?
2. Would it be best to develop a reliability metric not expressed in hours or years?

Power quality effects of SSL. We do not know what the effects of solid state lighting are on building power quality and, by extension, impacts on the grid. We need to study effects and mitigation strategies.

Grid-friendly performance mimics a resistive load such as an incandescent lamp: As the peak AC input voltage level decreases, the peak AC current decreases proportionally. Not grid-unfriendly performance, where as the peak AC input voltage decreases, the peak AC current rises proportionally until it drops abruptly to zero.

Existing research: Pacific Northwest National Laboratory (PNNL); Finelite, University of Colorado.

- *[Summaries of existing research pending]*

Key research questions:

1. How does SSL operation affect building-level power quality (partial building: system effects)?
2. What would be the impact on building power quality of full building SSL lighting strategy?
3. What are possible mitigation strategies of power quality problems from SSL?

Less expensive product testing. Cheaper equipment and methods for product performance testing is needed as approach for reducing overall product costs. Are there alternatives to LM-80, LM-79, etc. for validating performance?

Existing research: Pacific Northwest National Laboratory (PNNL), National Electrical Manufacturers Association (NEMA), U.S. Department of Energy (DOE), Energy Star, Design Lights Consortium.

- *[Summaries of existing research pending]*

Key research questions:

1. What equipment and methods are less expensive and accurate enough?
2. What is accurate enough?
3. What portion of total product cost is for testing?
4. What impact does the current testing needs have on time to market?
5. What accurate methods can be developed to project luminaire performance on similar luminaires in the product family?

Methods for predicting chromaticity maintenance using LM-80 data. There are no consensus methods for predicting long-term chromaticity maintenance. Better understanding of the factors that cause changes in chromaticity over time might allow development of models that could be used to predict chromaticity maintenance.

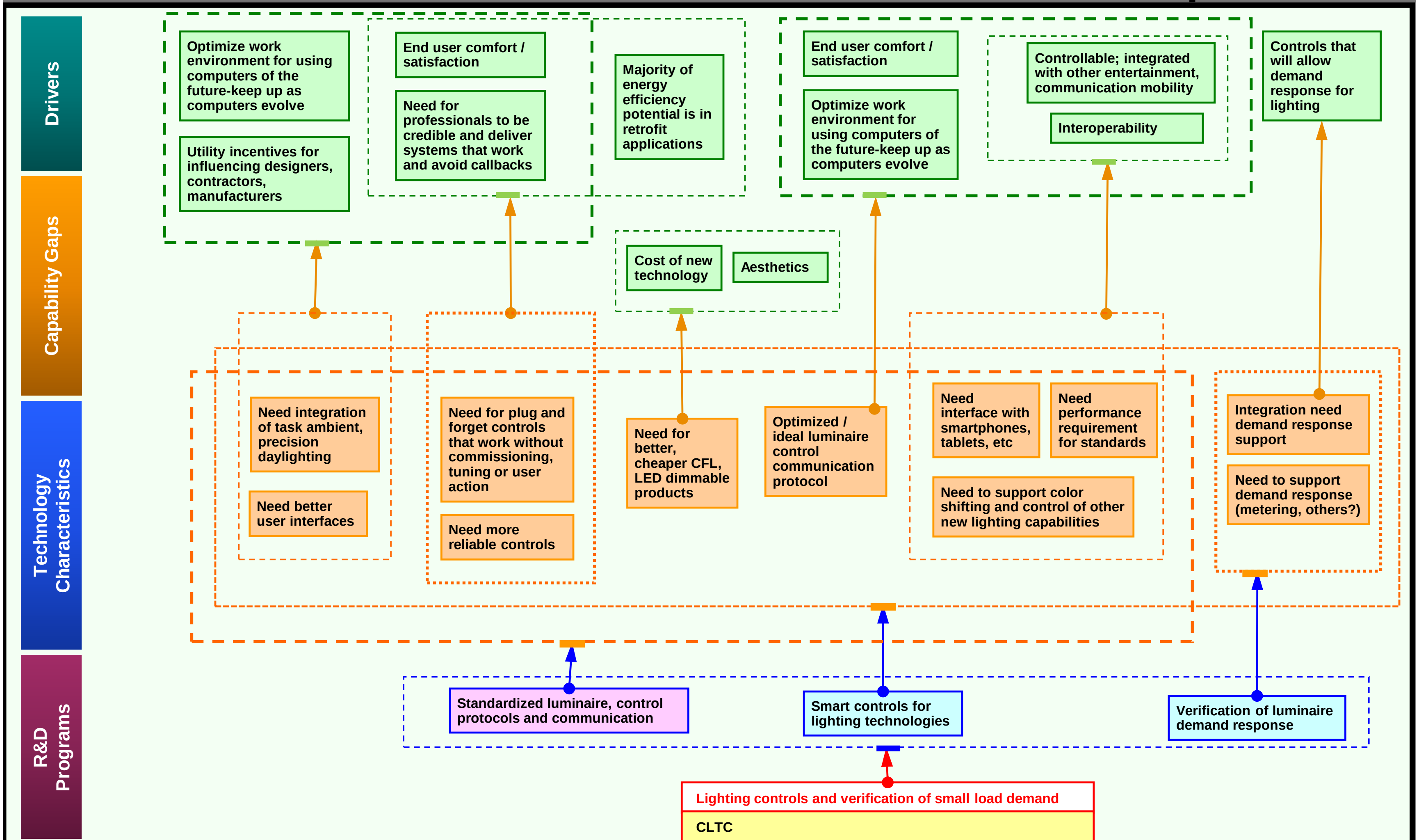
Existing research: None identified.

Key research questions:

1. What are the degradation factors in phosphors and what are their dependent variables?
2. What are the degradation factors in LEDs that cause changes in the wavelength of emissions, and what are their dependent variables?

Product/Service Area : **LIGHTING** *Energy Efficiency Technology Roadmap*

Technology Roadmap: **Lighting Controls (1 of 6)** *See "Technology Area Definitions" section*



Driver:		Commercially Available:		R&D Program Requirement:	No Explicit Systems Integration / Explicit Systems Integration
Capability Gap:		Commercially Unavailable:		Existing R&D Program or Project:	

R&D Program Summaries

Lighting controls and verification of small load demand. Provide research to quantify magnitude of demand response (DR) associated with lighting modification relative to DR call or event.

Existing research: University of California Davis California Lighting Technology Center (CLTC).

- *Summaries of existing research pending]*

Key research questions:

1. In response to a DR event, quantify and report amount of demand directly associated with DR call provided by lighting.
2. Define standard methodology for command, control and data exchange between lighting control systems and supplier?

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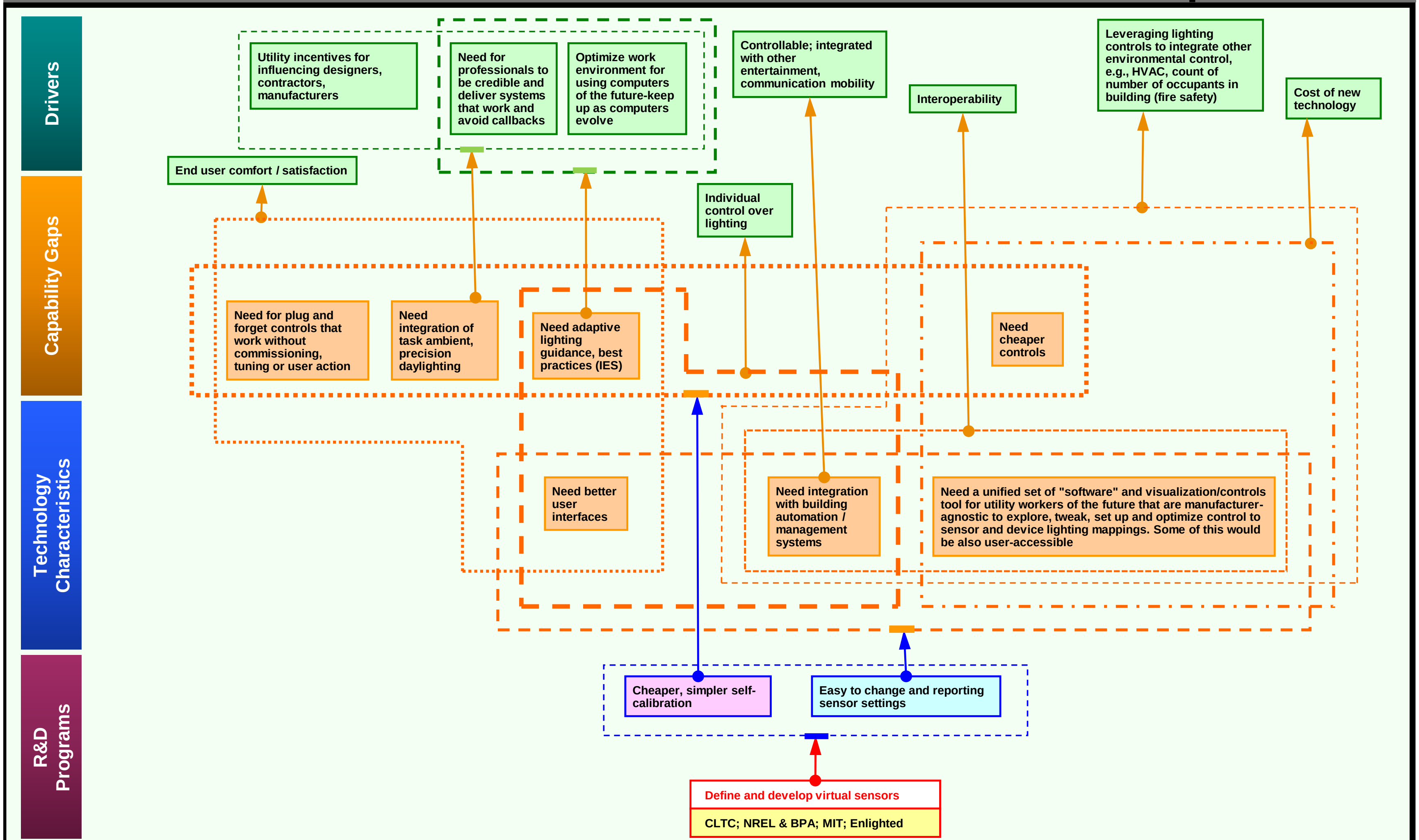
Product/Service Area : **LIGHTING**

Energy Efficiency Technology Roadmap

Technology Roadmap: **Lighting Controls (2 of 6)**

See "Technology Area Definitions" section



Driver: | Capability Gap: | Commercially Available: | Commercially Unavailable: | R&D Program Requirement: No Explicit Systems Integration | Explicit Systems Integration | Existing R&D Program or Project:

R&D Program Summaries

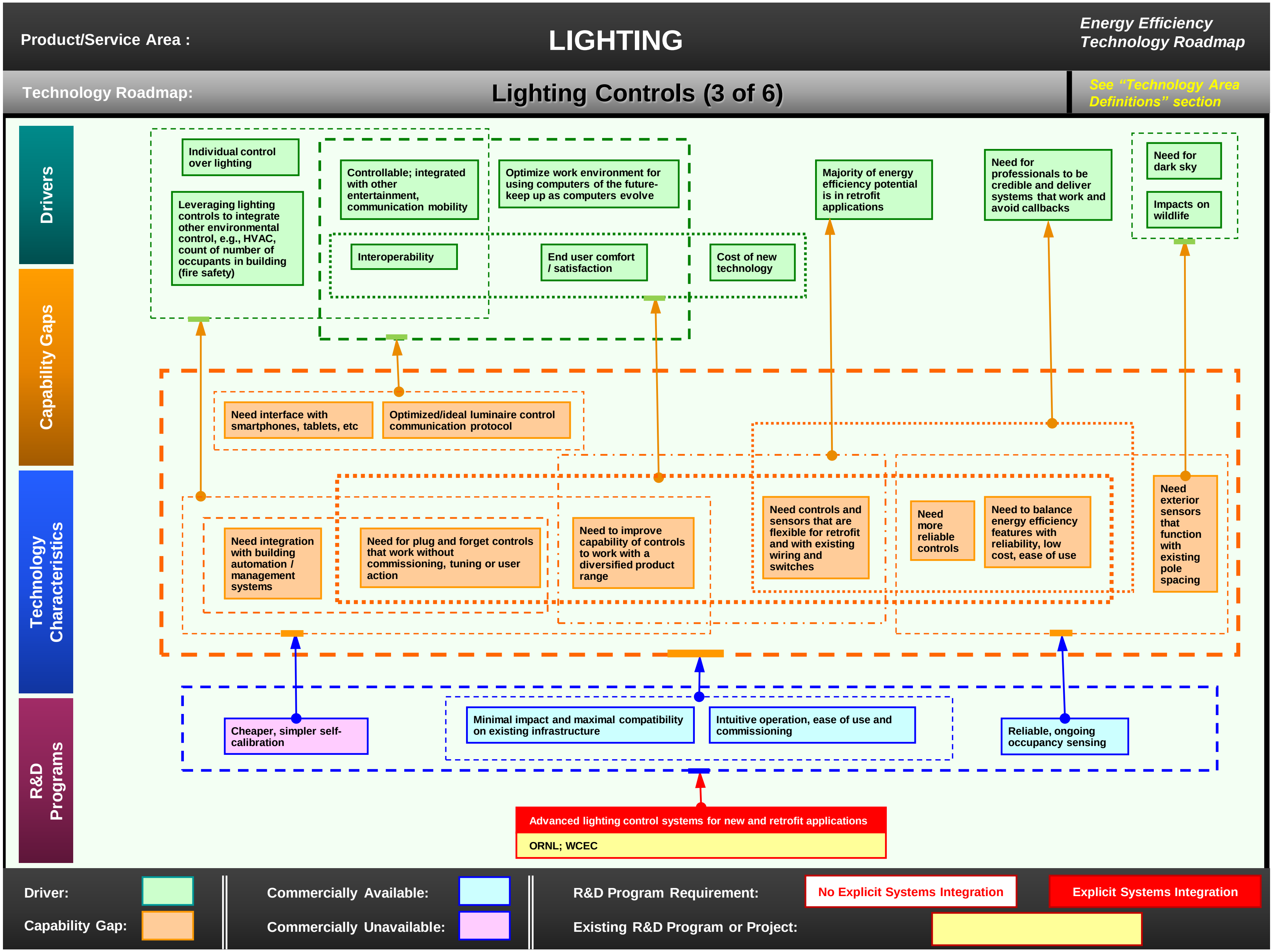
Define and develop virtual sensors. Some controls try to adjust settings according to the habits of the user. Cheaper, simpler, and more effective ways of doing this will be helpful. This will likely take advantage of better predictive modeling.

Existing research: Massachusetts Institute of Technology's (MIT), National Renewable Energy Laboratory (NREL) with the Bonneville Power Administration (BPA), Enlighted, University of California Davis California Lighting Technology Center (CLTC).

- The MIT Media Lab is currently researching feedback controlled solid state lighting, with a specific focus on low-cost solutions that sense and respond to human factors including user context, circadian rhythms, and productivity, and integrating these responses with atypical environmental factors. See Appendix B for more information.
- NREL is working on a project funded by the BPA Technology Innovation (TI) Office to develop an enhanced Image Processing Occupancy Sensor (IPOS) prototype. This is BPA TI Project #247, "Image Processing Occupancy Sensor (IPOS) Prototype Enhancement and Testing"; see Appendix B for more information.
- Enlighted (enlightedinc.com).
- *[Summaries of other existing research pending]*

Key research questions:

1. Determine/identify space characterization needs above and beyond basic occupancy.
2. Generate higher level sensor data to mitigate identified capability gaps. Example: use occupancy sensor and camera data to produce "traffic" information.
3. How to extract general context from virtual sensor data?
4. Develop self-commissioning systems for plug-and-play installation.



Product/Service Area :
LIGHTING
Energy Efficiency Technology Roadmap
Technology Roadmap:
Lighting Controls (3 of 6)
See "Technology Area Definitions" section
Drivers
Capability Gaps
Technology Characteristics
R&D Programs
Individual control over lighting
Leveraging lighting controls to integrate other environmental control, e.g., HVAC, count of number of occupants in building (fire safety)
Controllable; integrated with other entertainment, communication mobility
Optimize work environment for using computers of the future- keep up as computers evolve
Interoperability
End user comfort / satisfaction
Cost of new technology
Majority of energy efficiency potential is in retrofit applications
Need for professionals to be credible and deliver systems that work and avoid callbacks
Need for dark sky
Impacts on wildlife
Need interface with smartphones, tablets, etc
Optimized/ideal luminaire control communication protocol
Need integration with building automation / management systems
Need for plug and forget controls that work without commissioning, tuning or user action
Need to improve capability of controls to work with a diversified product range
Need controls and sensors that are flexible for retrofit and with existing wiring and switches
Need more reliable controls
Need to balance energy efficiency features with reliability, low cost, ease of use
Need exterior sensors that function with existing pole spacing
Cheaper, simpler self-calibration
Minimal impact and maximal compatibility on existing infrastructure
Intuitive operation, ease of use and commissioning
Reliable, ongoing occupancy sensing
Advanced lighting control systems for new and retrofit applications
ORNL; WCEC
Driver:
Capability Gap:
Commercially Available:
Commercially Unavailable:
R&D Program Requirement:
No Explicit Systems Integration
Explicit Systems Integration
Existing R&D Program or Project:

R&D Program Summaries

Advanced lighting control systems for retrofit applications. Leverage existing infrastructure (or legacy building system) rather than having to undertake a major retrofit/upgrade.

Existing research: University of California Davis California Lighting Technology Center (CLTC), Finelight.

- *[Summaries of existing research pending]*

Key research questions:

1. How do the advanced systems for retrofit tie into existing infrastructure?
2. What is the cost energy savings vs. energy left on the table comparisons?

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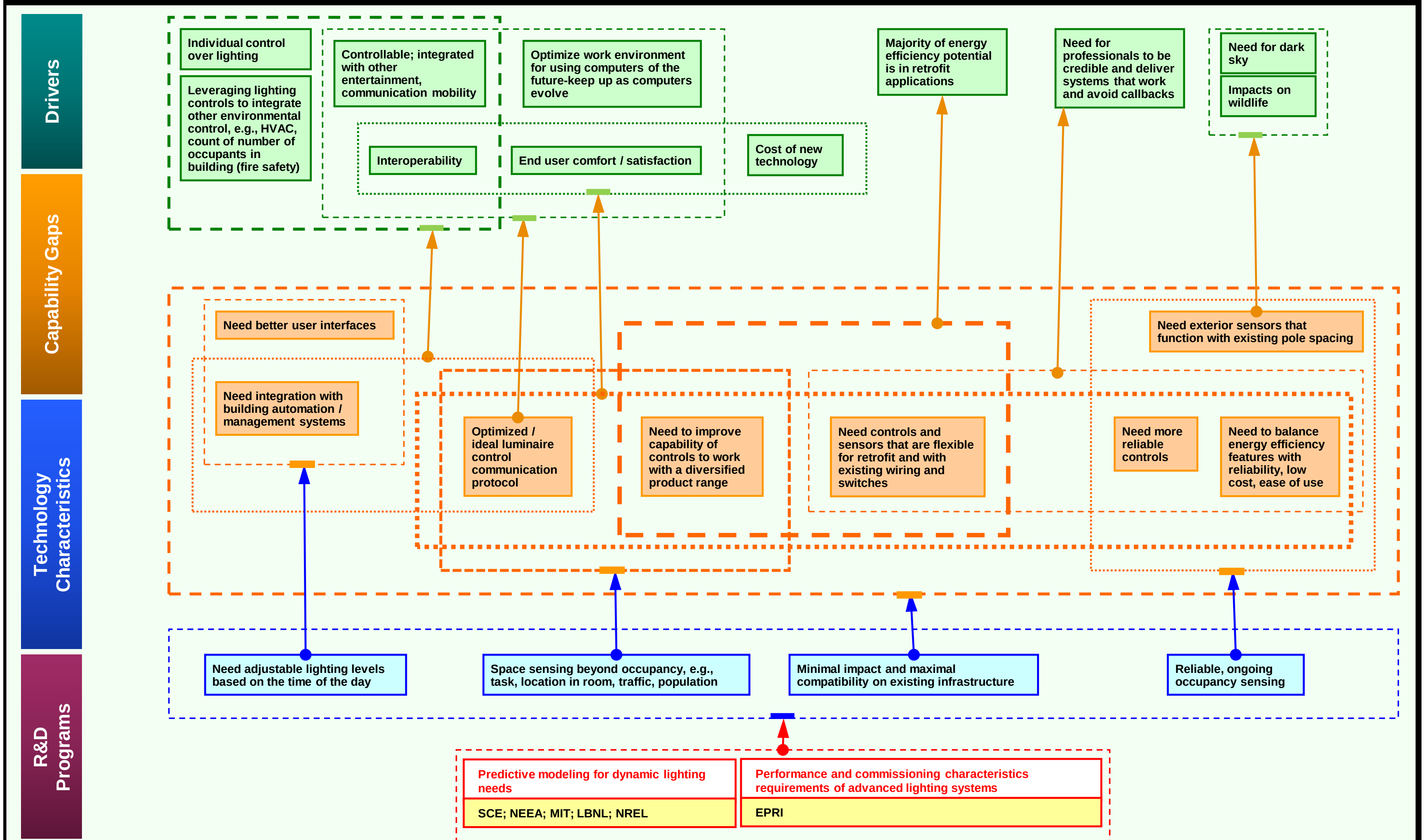
Product/Service Area : **LIGHTING**

Energy Efficiency Technology Roadmap

Technology Roadmap: **Lighting Controls (4 of 6)**

See "Technology Area Definitions" section



Driver: | Capability Gap: | Commercially Available: | Commercially Unavailable: | R&D Program Requirement: No Explicit Systems Integration / Explicit Systems Integration | Existing R&D Program or Project:

Performance and commissioning characteristics requirements of advanced lighting systems. Ties back to research project on failed controls installations and learning what not to do, developing performance standards and using these standards to assess lighting systems.

Existing research: Electric Power Research Institute (EPRI); Design Lights Consortium Commercial Advanced Lighting Controls (CALC)..

- For EPRI research in this area, see Appendix B.

Key research questions:

1. What are the steps needed to develop assessment protocols? Are there any protocols in place today?
2. How can assessment tools be integrated as part of user controls?

Predictive modeling for dynamic lighting needs. Research on modeling that will better predict lighting needs by taking into account the time of day and day of the week will make lighting controls more useful and more acceptable to users. Likely using predictive modeling developed from research being done at Massachusetts Institute of Technology's (MIT) Media Lab and possibly other institutions, integrate controls that predict lighting needs dynamically by taking into account the time of day and day of the week for the user will make lighting controls more useful and more acceptable to users.

Existing research: Researchers at Massachusetts Institute of Technology's (MIT) Media Lab, the University of California Davis California Lighting Technology Center (CLTC), the Lawrence Berkeley National Laboratory (LBNL), the Northwest Energy Efficiency Alliance (NEEA), and Southern California Edison (SCE) are among those doing work in this area. Subject matter experts have also indicated that R&D in this area may be ongoing at Watt Stopper and/or Lithonia Lighting..

- The MIT Media Lab is currently researching feedback controlled solid state lighting, with a specific focus on low-cost solutions that sense and respond to human factors including user context, circadian rhythms, and productivity, and integrating these responses with atypical environmental factors. See Appendix B for more information.
- Lithonia Lighting: http://www.lithonia.com/.
- CLTC work in this area includes researching exterior occupancy sensor networks to predict the direction and speed of pedestrians, cyclists and vehicles.
- For LBNL's research, see Appendix B.
- *[Summaries of other existing research pending]*

Key research questions:

1. How can predictive modeling for dynamic lighting needs help to create simpler calibration of systems?
2. When it comes to occupancy sensing, are we detecting people in the most optimal method?
3. How can spaces use knowledge of :
   a. Available luminaires?
   b. Available sensors?
   c. Pre-informed or determined via calibration) to produce optimal illumination automatically?

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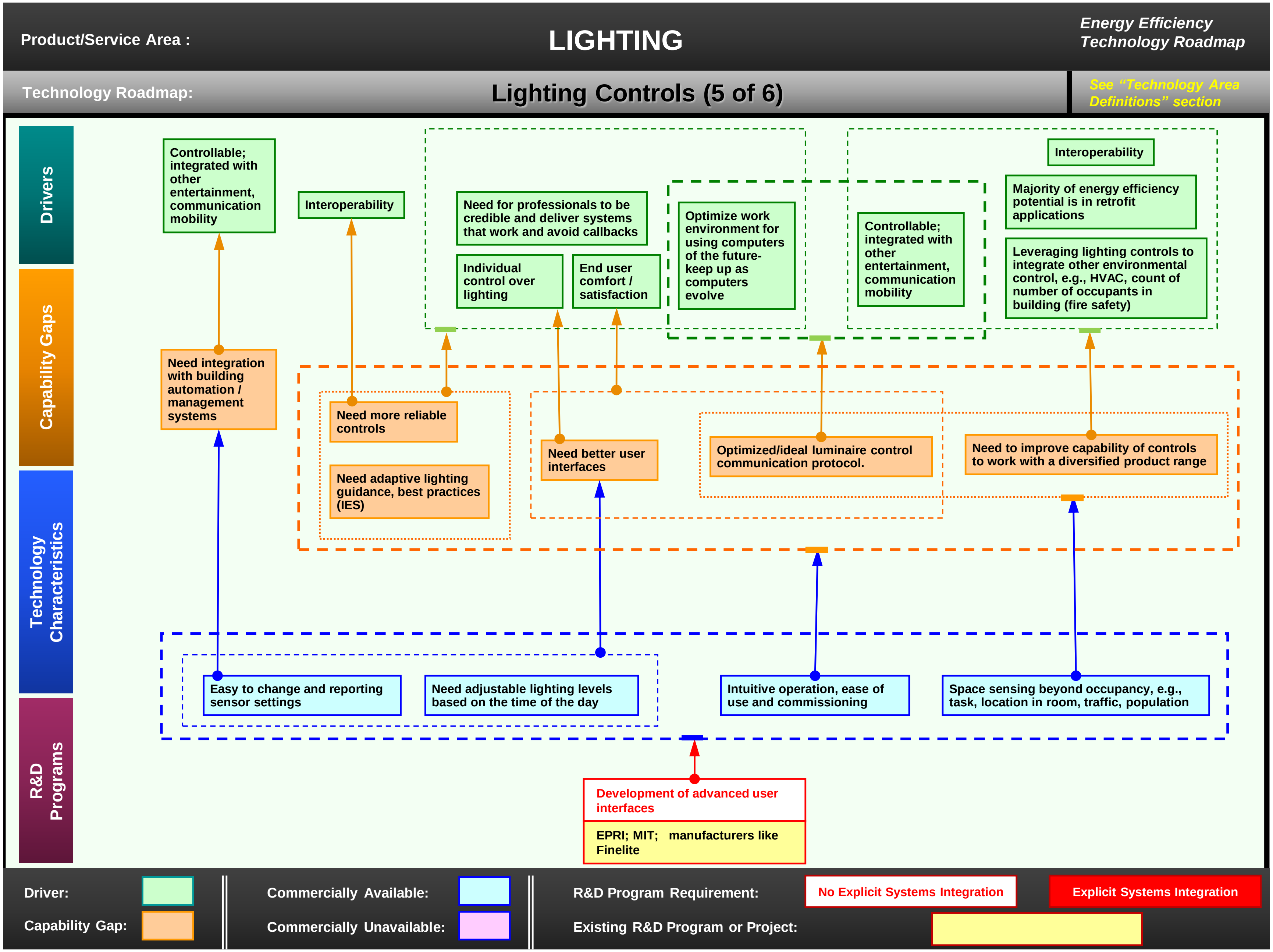

Product/Service Area :
LIGHTING
Energy Efficiency Technology Roadmap
Technology Roadmap:
Lighting Controls (5 of 6)
See "Technology Area Definitions" section
Drivers
Capability Gaps
Technology Characteristics
R&D Programs
Controllable; integrated with other entertainment, communication mobility
Interoperability
Need for professionals to be credible and deliver systems that work and avoid callbacks
Individual control over lighting
End user comfort / satisfaction
Optimize work environment for using computers of the future- keep up as computers evolve
Controllable; integrated with other entertainment, communication mobility
Interoperability
Majority of energy efficiency potential is in retrofit applications
Leveraging lighting controls to integrate other environmental control, e.g., HVAC, count of number of occupants in building (fire safety)
Need integration with building automation / management systems
Need more reliable controls
Need adaptive lighting guidance, best practices (IES)
Need better user interfaces
Optimized/ideal luminaire control communication protocol.
Need to improve capability of controls to work with a diversified product range
Easy to change and reporting sensor settings
Need adjustable lighting levels based on the time of the day
Intuitive operation, ease of use and commissioning
Space sensing beyond occupancy, e.g., task, location in room, traffic, population
Development of advanced user interfaces
EPRI; MIT; manufacturers like Finelite
Driver:
Capability Gap:
Commercially Available:
Commercially Unavailable:
R&D Program Requirement:
No Explicit Systems Integration
Explicit Systems Integration
Existing R&D Program or Project:

R&D Program Summaries

Development of advanced user interfaces. Develop methods that make controls intuitive and easy to use or transparent.

Existing research: Electric Power Research Institute (EPRI), Massachusetts Institute of Technology (MIT), manufacturers such as Finelight.

- For MIT's "Wristique" project, see Appendix B.
- *[Summaries of existing research pending]*

Key research questions:

1. Behavior analysis—what are the best methods for users to interact with lighting controls?
2. Individual recognition—non intrusive recognition system.
3. Rule making protocol—what rules needed to address interactions and differing commands between users?

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Product/Service Area :

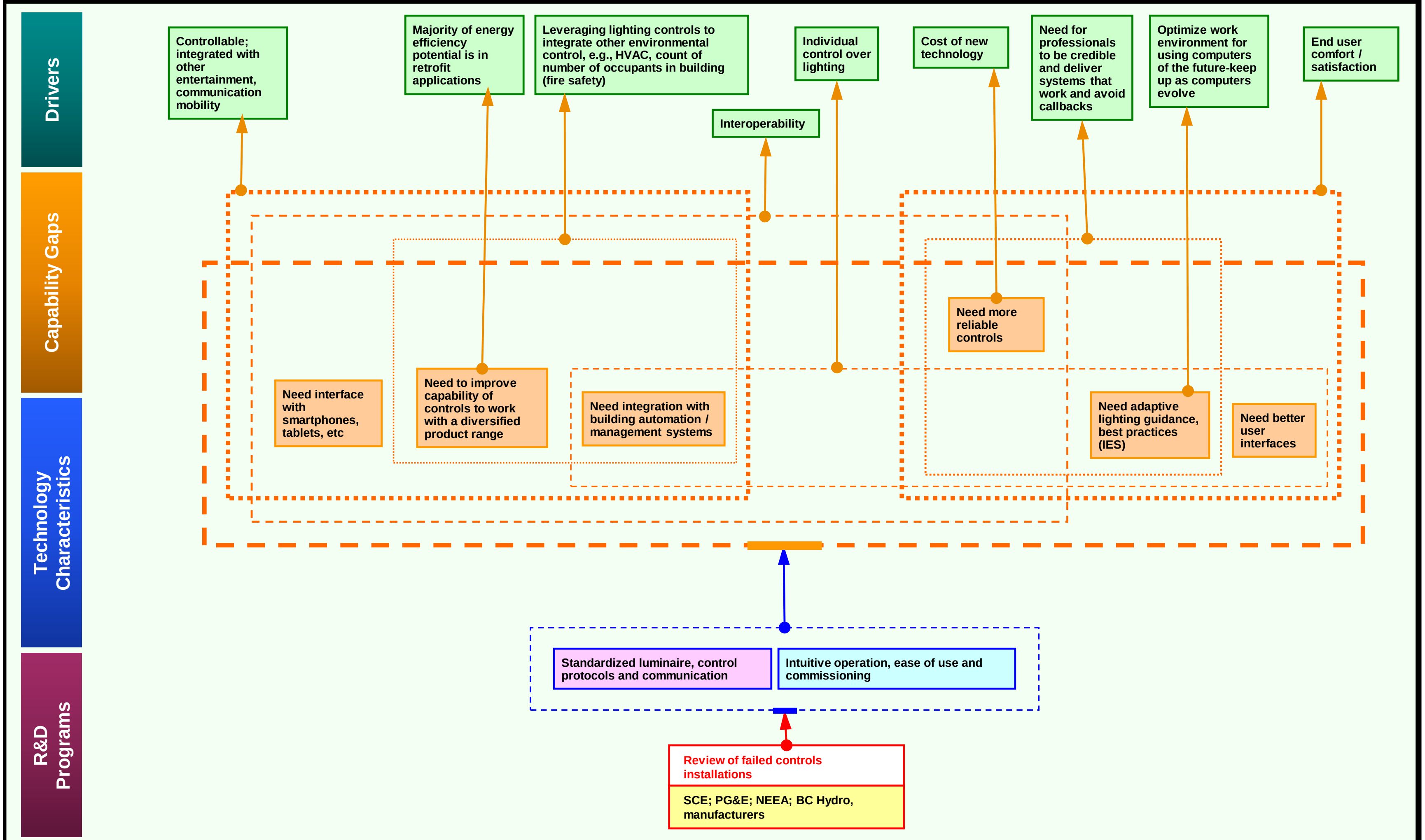
LIGHTING

Energy Efficiency Technology Roadmap

Technology Roadmap:

Lighting Controls (6 of 6)

See "Technology Area Definitions" section



Driver:		Commercially Available:		R&D Program Requirement:	No Explicit Systems Integration / Explicit Systems Integration
Capability Gap:		Commercially Unavailable:		Existing R&D Program or Project:	

R&D Program Summaries

Review of failed controls installations. Review failed controls projects to learn what not to do to enable end user comfort and satisfaction. Leverage information to help develop performance standards for control systems.

Existing research: Southern California Edison (SCE), Pacific Gas & Electric (PG&E), Northwest Energy Efficiency Alliance (NEEA), BC Hydro, and manufacturers.

- *[Summaries of existing research pending]*

Key research questions:

1. How many failed controls projects are there?
2. Why did they fail?
3. What could have been done to prevent the failure?
4. How can this information be leveraged for technology?

Product/Service Area :

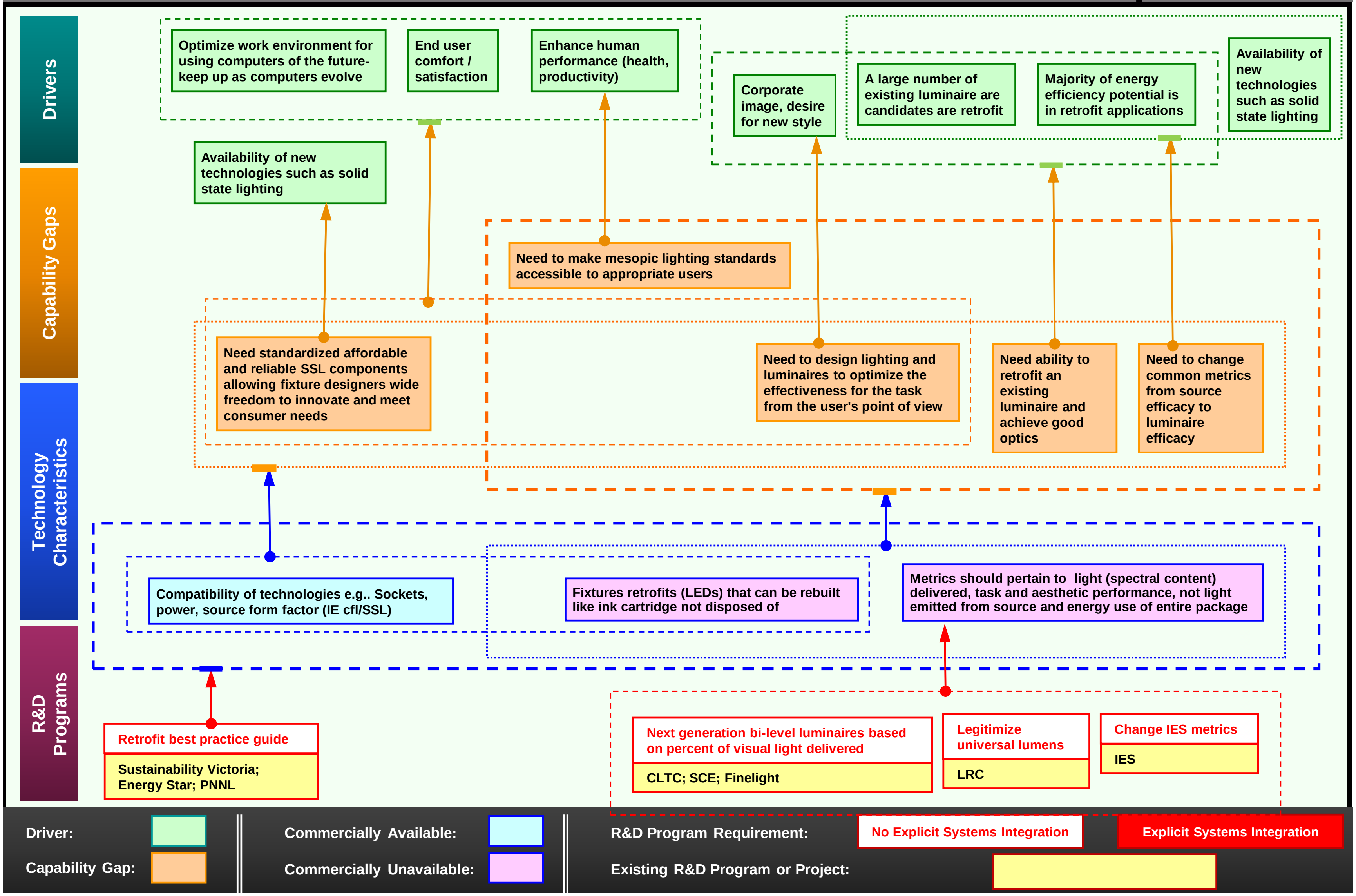
LIGHTING

Energy Efficiency Technology Roadmap

Technology Roadmap:

Luminaires

See "Technology Area Definitions" section



R&D Program Summaries

Retrofit best practice guide.
Methodology for designing whether to replace luminaires, relamp, or retrofit components decision tree (flow chart).

Existing research: Sustainability Victoria, Energy Star, Pacific NW National Laboratory (PNNL).

- *[Summaries of existing research pending]*

Key research questions:

1. Key performance criteria.
2. What to do, when to do it, how to do it?

Legitimize Universal Lumens.
For Universal Lumens, to be fully accepted by the market, needs to have standards changed to legitimize it. Provide data to support Illuminating Engineering Society (IES) standards modifications.

Existing research: Bonneville Power Administration (BPA), Rensselaer Polytechnic Institute Lighting Research Center (LRC), Southern California Edison (SCE).

- BPA and LRC are collaborating on research in this area during 2015-2016 in a project titled "Demonstration of Outdoor Lighting for Maximizing Perceptions of Safety and Security" (BPA designation Technology Innovation Project (TIP) # 329).
- *[Summaries of other existing research pending]*

Key research questions:

1. The BPA / LRC project (TIP 329) consists of a full-scale outdoor lighting demonstration at a parking lot facility. It is based on a proposed specification method for maximizing perceptions of safety and security by occupants, taking advantage of the differential spectral (color) sensitivity of the human visual system for brightness perception at nighttime light levels. Sensations of brightness are in turn strongly related to perceptions of personal safety and security in outdoor locations. It is anticipated that using "white" light sources such as light emitting diode (LED) illumination, in place of conventional high pressure sodium (HPS) illumination, that energy savings of 40%-50% will be possible while maintaining perceptions of brightness, safety and security.

Change Illuminating Engineering Society (IES) metrics.
Metrics and standards have evolved as we learn more about how humans use light most effectively. More work needs to be done to continue to improve Illuminating Engineering Society (IES) metrics.

Existing research: Illuminating Engineering Society (IES) .

- IES: http://www.iesna.org/.

Key research questions:

1. Questions not yet specified.

Next generation bi-level luminaires based on percent of visual light delivered.
Determine if 15% light-level is sufficient for non-occupied stairwells and corridors. 15% is estimate of lowest "acceptable" light-level combined with lowest-cost / easiest to deliver light level. Research could set a different level.

Existing research: University of California Davis California Lighting Technology Center (CLTC), Southern California Edison (SCE), Finelight.

- *[Summaries of existing research pending]*

Key research questions:

1. Will people accept a "bi-level" stairwell and corridor lighting approach where occupancy motion = 100%light level non occupancy no-motion = 15% light level? If so, SSL luminaires should need only 3% - 5% power when space is not occupied.
2. Integrate this research with fire code requirements.

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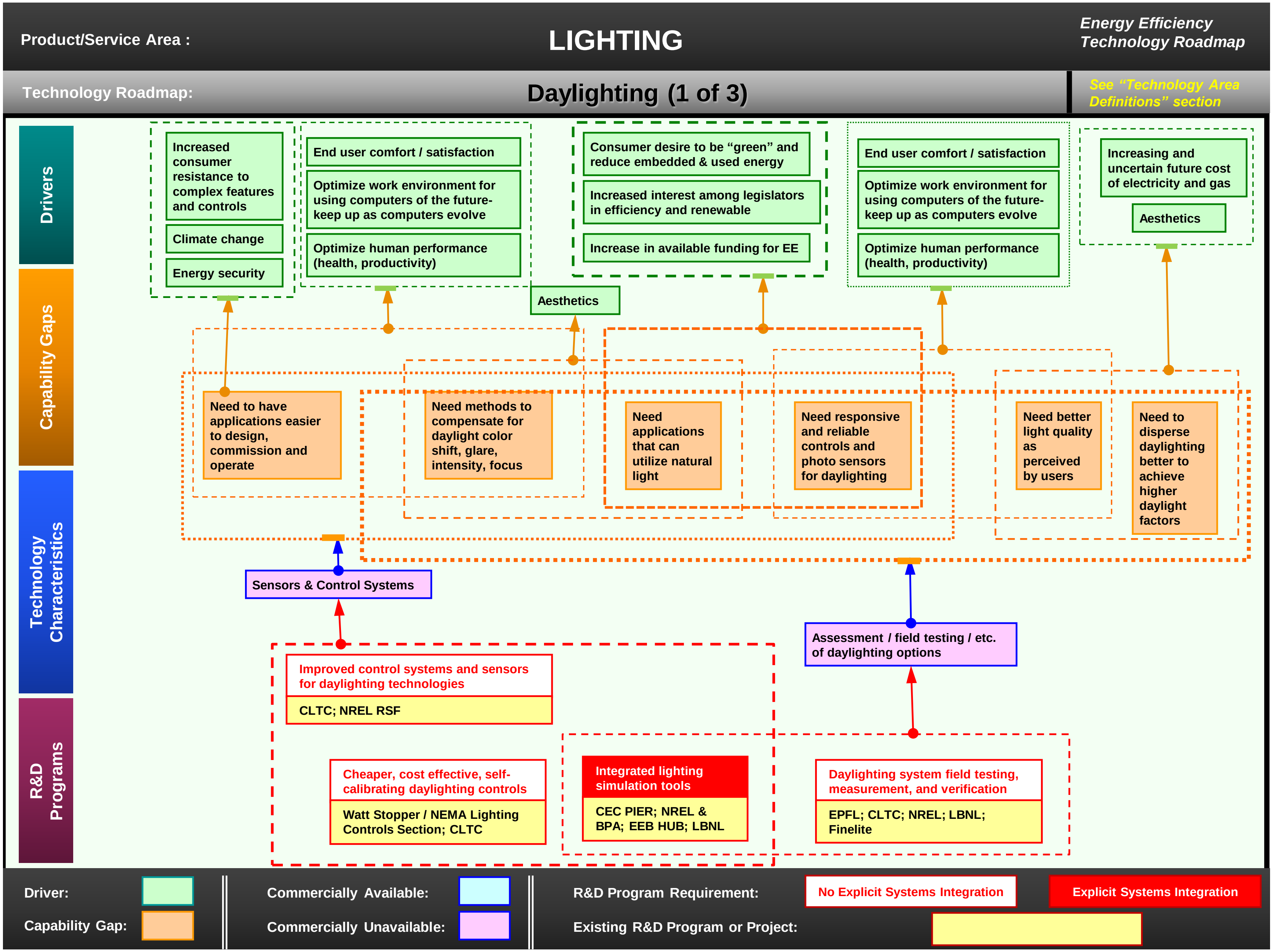
Product/Service Area :
LIGHTING
Energy Efficiency Technology Roadmap
Technology Roadmap:
Daylighting (1 of 3)
See "Technology Area Definitions" section
Drivers
Capability Gaps
Technology Characteristics
R&D Programs
Increased consumer resistance to complex features and controls
Climate change
Energy security
End user comfort / satisfaction
Optimize work environment for using computers of the future- keep up as computers evolve
Optimize human performance (health, productivity)
Aesthetics
Consumer desire to be "green" and reduce embedded & used energy
Increased interest among legislators in efficiency and renewable
Increase in available funding for EE
End user comfort / satisfaction
Optimize work environment for using computers of the future- keep up as computers evolve
Optimize human performance (health, productivity)
Increasing and uncertain future cost of electricity and gas
Aesthetics
Need to have applications easier to design, commission and operate
Need methods to compensate for daylight color shift, glare, intensity, focus
Need applications that can utilize natural light
Need responsive and reliable controls and photo sensors for daylighting
Need better light quality as perceived by users
Need to disperse daylighting better to achieve higher daylight factors
Sensors & Control Systems
Assessment / field testing / etc. of daylighting options
Improved control systems and sensors for daylighting technologies
CLTC; NREL RSF
Cheaper, cost effective, self-calibrating daylighting controls
Watt Stopper / NEMA Lighting Controls Section; CLTC
Integrated lighting simulation tools
CEC PIER; NREL & BPA; EEB HUB; LBNL
Daylighting system field testing, measurement, and verification
EPFL; CLTC; NREL; LBNL; Finelite
Driver:
Capability Gap:
Commercially Available:
Commercially Unavailable:
R&D Program Requirement:
No Explicit Systems Integration
Explicit Systems Integration
Existing R&D Program or Project:

R&D Program Summaries

Integrated lighting simulation tools. Develop high quality, validated lighting tools for daylighting design. Tools should be capable of simulating daylight, electric light, lighting controls, complex fenestration systems, and inform a whole building energy model.

Existing research: Stakeholders have indicated that there is ongoing research in this area at the California Energy Commission's (CEC) Public Interest Energy Research (PIER) program as well as at the National Renewable Energy Laboratory (NREL)—with the Bonneville Power Administration, Energy Efficient Buildings Hub (EEB HUB), and the Lawrence Berkeley National Laboratory (LBNL.).

- NREL is working on a project funded by the Bonneville Power Administration (BPA) Technology Innovation (TI) Office to study the feasibility of integrating building energy models for new and existing buildings that evaluates daylighting as a viable energy efficiency strategy and that can be analyzed using emerging building energy efficiency metrics such as the Energy Utilization Index (EUI). This is BPA TI Project #252,"Integrated Daylighting and Energy Analysis Toolkit (IDEAKit)"; See Appendix B for more information.
- *[Summaries of other existing research pending]*

Key research questions:

1. How can we characterize complex fenestration devices at a resolution fine enough to accurately capture daylight redirection devices?
2. How can we improve existing simulation tools to improve accuracy and speed of execution?
3. How can we scale existing control simulation tools (e.g. DAYSIM, OpenStudio, SPOT) to the whole building level?
4. How can we improve the capture, delivery, and dissemination of materials and systems performance to simulation engineers?
5. How can tools be leveraged for large scale, sector-wide daylighting analyses?

Improved control systems and sensors for daylighting technologies. Explore alternative ways of sensing daylight and adjust the electric lights accordingly. (Separate paths for top lighting from side lighting).

Existing research: University of California Davis California Lighting Technology Center (CLTC), National Renewable Energy Laboratory (NREL) Research Support Facility (RSF), industry research.

- For the CLTC's work in this area, see Appendix B.
- *[Summaries of other existing research pending]*

Key research questions:

1. How do we improve reliability and cost in daylighting sensing?
2. How do we automate calibration and account for occupant needs and desires?
3. How do we integrate lighting, fenestration and HVAC controls?

Continued . . .

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Cheaper, cost effective, self-calibrating daylighting controls. Making daylighting cost-effective continues to be a challenge. Easier to use, and self-calibrating controls can help to make daylighting more attractive.

Existing research: Subject matter experts indicated that research was ongoing at the Lighting Research Center (LRC), and possibly at Watt Stopper and under the aegis of the Lighting Controls Section of the Association of Electrical Equipment and Medical Imaging Manufacturers (NEMA); R&D is also ongoing at the California Lighting Technology Center (CLTC).

- Watt Stopper is researching dual-loop daylight control systems that self commission and offer continual calibration (http://cltc.ucdavis.edu/content/view/142/164/).
- The Lighting Research Center's (LRC) Capturing the Daylight Dividend program has completed R&D on daylighting systems and controls, and has also worked on a number of case studies. (http://www.lrc.rpi.edu/researchAreas/daylighting.asp).
- Information about CLTC research in this area can be found in Appendix B.

Key research questions:

1. How do we develop integrated sensor and control systems for plug and play daylight harvesting with skylights and windows?

Daylighting system field testing, measurement, and verification. Need to develop and agree upon measurement protocols to fairly and consistently evaluate daylighting strategies and components.

Existing research: Research ongoing at the Swiss École Polytechnique Fédérale de Lausanne (EPFL), UC Davis California Lighting Technology Center (CLTC), National Renewable Energy Laboratory (NREL), and Finelight.

- NREL's Building Agent project (see M. Schott, N. Long, J. Scheib, K. Fleming, K. Benne, and L. Brackney, "Progress on Enabling an Interactive Conversation Between Commercial Building Occupants and Their Building to Improve Comfort and Energy Efficiency," NREL Conference Paper 5500-55197, 2012, http://www.nrel.gov/buildings/pdfs/55197.pdf).
- *[Summaries of other existing research pending]*

Key research questions:

1. How can we leverage HDRI to characterize daylighting systems?
2. How can we capture the occupant experience?

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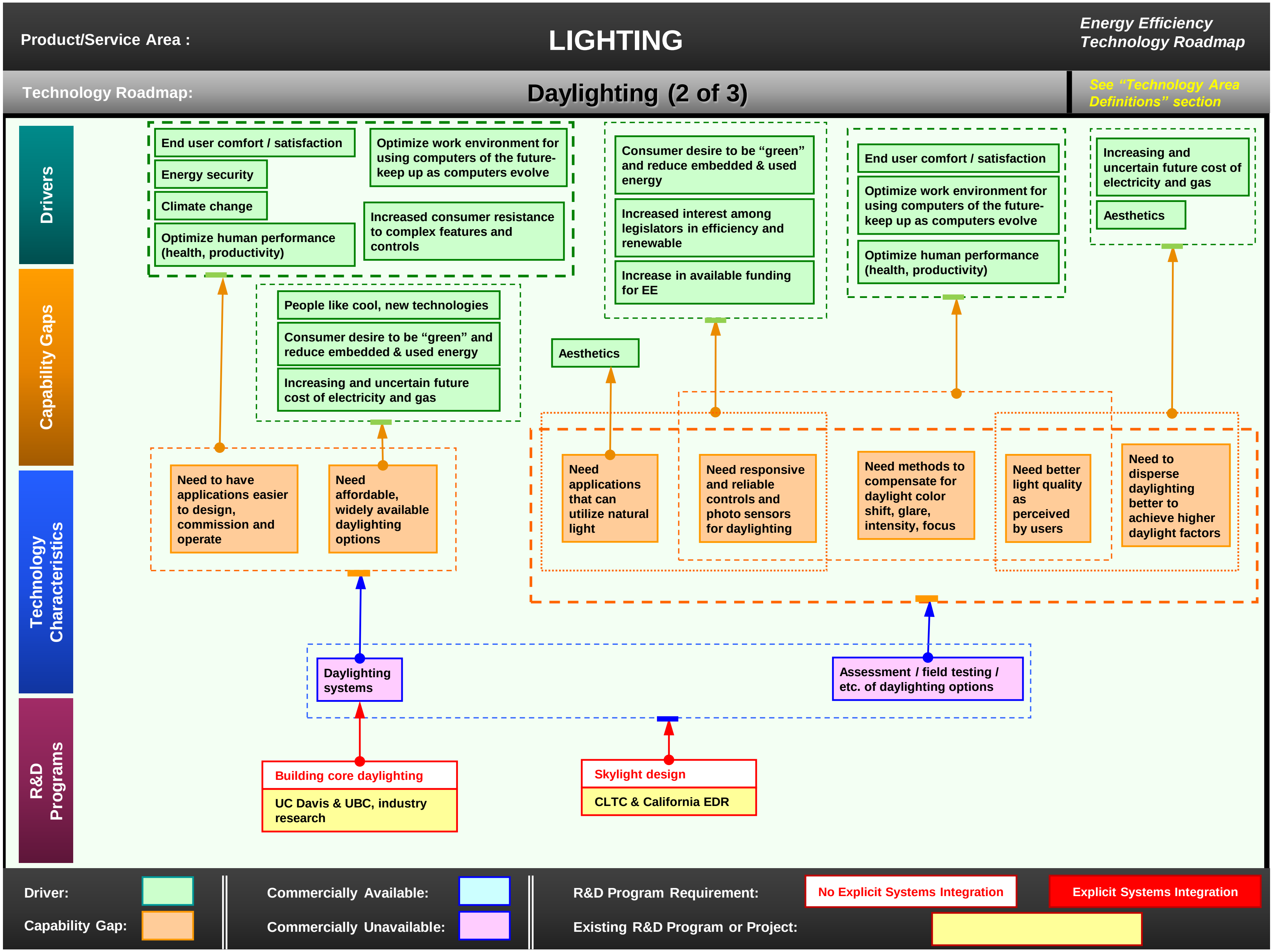

Product/Service Area :
LIGHTING
Energy Efficiency Technology Roadmap
Technology Roadmap:
Daylighting (2 of 3)
See "Technology Area Definitions" section
Drivers
Capability Gaps
Technology Characteristics
R&D Programs
End user comfort / satisfaction
Energy security
Climate change
Optimize human performance (health, productivity)
Optimize work environment for using computers of the future-keep up as computers evolve
Increased consumer resistance to complex features and controls
People like cool, new technologies
Consumer desire to be "green" and reduce embedded & used energy
Increasing and uncertain future cost of electricity and gas
Consumer desire to be "green" and reduce embedded & used energy
Increased interest among legislators in efficiency and renewable
Increase in available funding for EE
End user comfort / satisfaction
Optimize work environment for using computers of the future-keep up as computers evolve
Optimize human performance (health, productivity)
Increasing and uncertain future cost of electricity and gas
Aesthetics
Aesthetics
Need to have applications easier to design, commission and operate
Need affordable, widely available daylighting options
Need applications that can utilize natural light
Need responsive and reliable controls and photo sensors for daylighting
Need methods to compensate for daylight color shift, glare, intensity, focus
Need better light quality as perceived by users
Need to disperse daylighting better to achieve higher daylight factors
Daylighting systems
Assessment / field testing / etc. of daylighting options
Building core daylighting
UC Davis & UBC, industry research
Skylight design
CLTC & California EDR
Driver:
Capability Gap:
Commercially Available:
Commercially Unavailable:
R&D Program Requirement:
No Explicit Systems Integration
Explicit Systems Integration
Existing R&D Program or Project:

R&D Program Summaries

Building core daylighting.

Daylighting has traditionally concentrated on perimeter zones (near windows). Bringing daylighting into the core of buildings i.e. areas away from windows and skylights.

Existing research: There is an ongoing research partnership between the University of British Columbia (UBC) and the California Lighting Technology Center (CLTC) to provide daylighting in core zones, but more research is needed to find more affordable and effective ways of doing this. Firms in the industry are conducting research also, as is the Lawrence Berkeley National Laboratory (LBNL).

- The CLTC is currently working on an R&D project to evaluate the application of UBC's Core Sunlighting System to the climate and topography of California's Central Valley. See Appendix B for more information on this effort.
- For LBNL's work in this area, see Appendix B.
- *[Summaries of other existing research pending]*

Key research questions:

1. How do we collect?
2. How do we transport?
3. How do we deliver?
4. How do we integrate with electric lighting?

Skylight design.

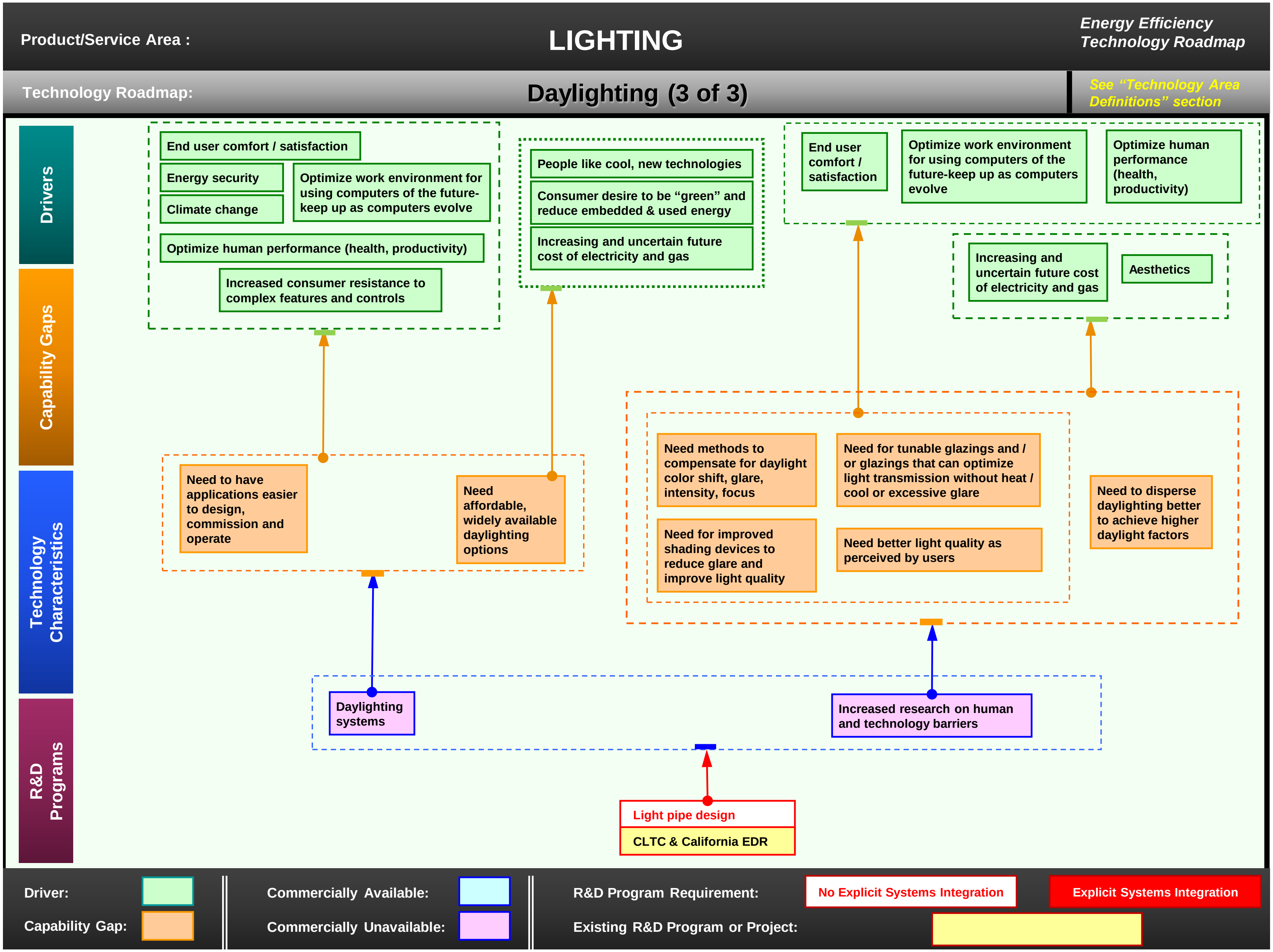
Making daylighting cost-effective continues to be a challenge. Effective, affordable, leak-resistant skylight design could help make daylighting easier and more affordable to adopt.

Existing research: The California Lighting Technology Center (CLTC) is engaged in ongoing R&D in this area, and California Energy Design Resources (EDR) website provides a list of skylight and daylighting resources.

- Information about CLTC's ongoing research into sunlighting and solatube skylight systems can be found in Appendix B.
- California's utility ratepayers fund the state's EDR program; Southern California Edison administers the program under the auspices of the California Public Utilities Commission (CPUC). The EDR website serves as a portal for architects, engineers, lighting designers, and developers to access energy design tools and resources that will foster energy-efficient commercial and industrial building design. EDR resources include daylighting and sky light design (http://www.energydesignresources.com/technology/daylighting-design.aspx, http://www.energydesignresources.com/resources/publications/design-briefs/design-brief-skylights-with-suspended-ceilings.aspx).

Key research questions:

1. Questions not yet specified.



Product/Service Area :
LIGHTING
Energy Efficiency Technology Roadmap
Technology Roadmap:
Daylighting (3 of 3)
See "Technology Area Definitions" section
Drivers
Capability Gaps
Technology Characteristics
R&D Programs
End user comfort / satisfaction
Energy security
Climate change
Optimize work environment for using computers of the future-keep up as computers evolve
Optimize human performance (health, productivity)
Increased consumer resistance to complex features and controls
People like cool, new technologies
Consumer desire to be "green" and reduce embedded & used energy
Increasing and uncertain future cost of electricity and gas
End user comfort / satisfaction
Optimize work environment for using computers of the future-keep up as computers evolve
Optimize human performance (health, productivity)
Increasing and uncertain future cost of electricity and gas
Aesthetics
Need to have applications easier to design, commission and operate
Need affordable, widely available daylighting options
Need methods to compensate for daylight color shift, glare, intensity, focus
Need for tunable glazings and / or glazings that can optimize light transmission without heat / cool or excessive glare
Need for improved shading devices to reduce glare and improve light quality
Need better light quality as perceived by users
Need to disperse daylighting better to achieve higher daylight factors
Daylighting systems
Increased research on human and technology barriers
Light pipe design
CLTC & California EDR
Driver:
Capability Gap:
Commercially Available:
Commercially Unavailable:
R&D Program Requirement:
No Explicit Systems Integration
Explicit Systems Integration
Existing R&D Program or Project:

R&D Program Summaries

Light pipe design. (Summary not yet provided.)

Existing research: University of California Davis and California Energy Design Resources (EDR).

- *[Summaries of existing research pending]*

Key research questions:

1. Questions not yet specified.

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Commercial Lighting: Advanced Controls

Light-emitting diode (LED) technology is on a path to become ubiquitous in the commercial sector. Advanced lighting controls complement this diffusion in a number of ways, such as:

- Non-energy benefits that may soon relegate energy savings considerations to the sidelines.
- Opportunities for low-cost energy performance metering to provide robust energy savings verification.

From a utility perspective, energy saving incentives for simple standalone LED lights currently exist in an extremely dynamic market and are unlikely to last forever, because prices are dropping so fast. Advanced lighting controls will offer additional opportunities for energy savings, beyond simple LED lights. However, current products have very low market penetration and need further improvements.

In the commercial sector within the Pacific Northwest, the long-term (10+ year) vision for lighting and advanced controls is that most new construction and major renovation projects will use Zero Net Energy (ZNE) design & construction as the obvious, least-cost, least-risk choice. Advanced lighting controls and daylight harvesting appear to be essential components of most ZNE buildings built to date. Many commercial spaces in the Pacific Northwest have minimal daylight access, so the alternative energy-saving strategy of task / ambient / vertical / dynamic-color lighting may be needed in some spaces. This vision will develop from a foundation of short-term and medium-term goals.

Utilities can contribute to progress toward this long-term vision through strategic technology research, development, and demonstration to achieve the following short- and medium-term visions:

Short-term (0-5 years): Incentivizing, specifying, purchasing, installing, programming, commissioning, operating, and verifying advanced lighting controls that save energy is "as easy as screwing in a light bulb."

Medium-term (5-10 years): Interoperability enables non-energy benefits that drive market adoption. To ensure that utilities can verify energy savings, performance metering becomes a simple solution to multiple challenges.

Investing in technology research based on these short- and medium-term goals will be of value to BPA and regional stakeholders whether or not the long-term vision articulated above is fully realized. The market is extremely dynamic, which means that today's research decisions to achieve the 10+ year vision will need to be adjusted as new information is learned, but progress generally toward this longer-term vision will foster technology advancements best suited to serve utility and rate payer needs in the Pacific Northwest.

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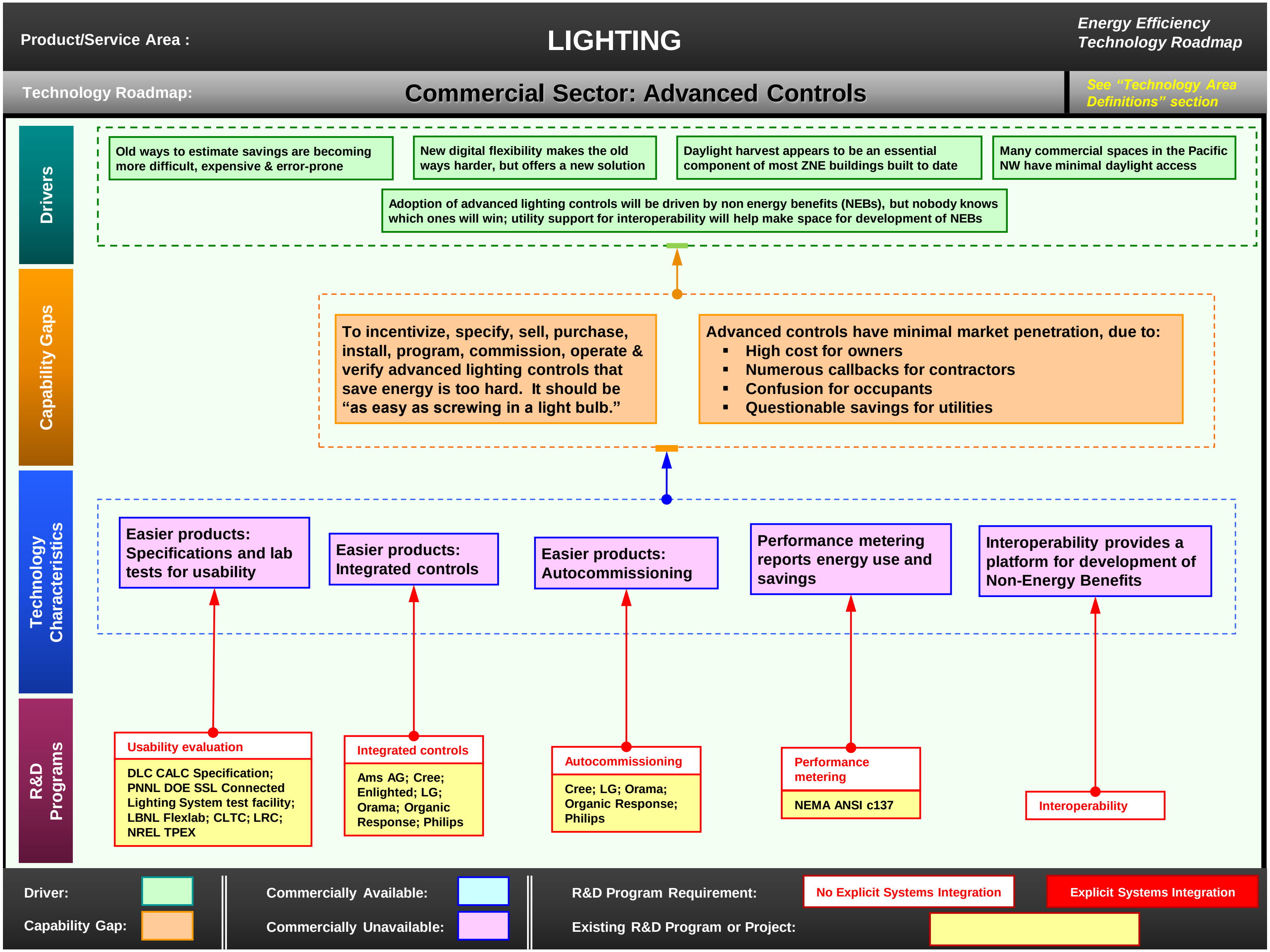

Product/Service Area :
LIGHTING
Energy Efficiency Technology Roadmap
Technology Roadmap:
Commercial Sector: Advanced Controls
See "Technology Area Definitions" section
Drivers
Old ways to estimate savings are becoming more difficult, expensive & error-prone
New digital flexibility makes the old ways harder, but offers a new solution
Daylight harvest appears to be an essential component of most ZNE buildings built to date
Many commercial spaces in the Pacific NW have minimal daylight access
Adoption of advanced lighting controls will be driven by non energy benefits (NEBs), but nobody knows which ones will win; utility support for interoperability will help make space for development of NEBs
Capability Gaps
To incentivize, specify, sell, purchase, install, program, commission, operate & verify advanced lighting controls that save energy is too hard. It should be "as easy as screwing in a light bulb."
Advanced controls have minimal market penetration, due to:
▪ High cost for owners
▪ Numerous callbacks for contractors
▪ Confusion for occupants
▪ Questionable savings for utilities
Technology Characteristics
Easier products: Specifications and lab tests for usability
Easier products: Integrated controls
Easier products: Autocommissioning
Performance metering reports energy use and savings
Interoperability provides a platform for development of Non-Energy Benefits
R&D Programs
Usability evaluation
DLC CALC Specification; PNNL DOE SSL Connected Lighting System test facility; LBNL Flexlab; CLTC; LRC; NREL TPEX
Integrated controls
Ams AG; Cree; Enlighted; LG; Orama; Organic Response; Philips
Autocommissioning
Cree; LG; Orama; Organic Response; Philips
Performance metering
NEMA ANSI c137
Interoperability
Driver:
Capability Gap:
Commercially Available:
Commercially Unavailable:
R&D Program Requirement:
No Explicit Systems Integration
Explicit Systems Integration
Existing R&D Program or Project:

R&D Program Summaries

Autocommissioning. In commercial spaces under 50,000 sf, where support by highly trained technicians is not affordable, make Advanced Lighting Controls "Plug and Play", to deliver appropriate light when and where needed, while saving energy.

Existing research: Research ongoing at manufacturers Cree (lighting.cree.com), LG (www.lglightingus.com), Orama (www.oramainc.com), Organic Response (organicresponse.com), and Philips (www.usa.lighting.philips.com).

Key research questions:

1. How can initialization/commissioning occur automatically over the first few weeks of operation, with minimal installer/operator expertise?
2. How can product performance adapt to changing operational needs & system capabilities, without operator expertise?
3. How can any remaining needs for expertise be met remotely or with minimal training?
4. Will the residential consumer market drive innovation that migrates into small/medium commercial spaces?

Usability evaluation. Shorten the feedback loop for product release/evaluation/revision that currently depends on multi-year field tests of new Advanced Lighting Control products.

Existing research: Research ongoing at Design Lights Consortium (DLC); Pacific Northwest National Laboratory (PNNL); Lawrence Berkeley National Laboratory (LBNL); California Lighting Technology Center (CLTC); Rensselaer Polytechnic Institute Lighting Research Center (LRC); and National Renewable Energy Laboratory (NREL).

- DLC CALC Specification: https://www.designlights.org/content/CALC/SpecificationAndQPL.
- PNNL Department of Energy SSL Connected Lighting System test facility: http://energyenvironment.pnnl.gov/research_areas/research_area_description.asp?id=174.
- LBNL FLEXLAB: https://flexlab.lbl.gov/.
- CLTC: cltc.ucdavis.edu.
- LRC: www.lrc.rpi.edu.
- NREL Technology Performance Exchange (TPEX): www.tpex.org.

Key research questions:

1. How can new products be evaluated for satisfaction of various stakeholders (design/specify, install, commission, occupants, operations & maintenance, IT, energy efficiency programs), quickly and at minimal expense?
2. How can test results be made available to a broad range of users?
3. As one example of an evaluation criterion, how can firmware be updated quickly, easily, automatically in large and small installations?

Performance metering. The energy saved by Advanced Lighting Controls varies widely by application, product, site, and parametric settings. Efficiency programs need reliable data about energy savings from incented products, without expensive and disruptive site visits for datalogging.

Existing research: The National Electrical Manufacturers Association (NEMA) sponsors the work of the American National Standards Institute's (ANSI) Committee 137.

- NEMA's Lighting Systems Division sponsors the work of the Lighting Systems Committee (C137) developing standards and specifications for indoor and outdoor lighting systems that considers human health and comfort, personal security, the physical environment, energy consumption, and daylight integration; see https://www.nema.org/Technical/Pages/ANSI-C137-Lighting-Systems-Committee.aspx.

Key research questions:

1. How best can accurate, reliable & useful data about energy savings be collected and transferred from luminaires to efficiency programs, at low cost to all participants, while addressing concerns about privacy & security?
2. How best can embedded meters self-calibrate, and maintain calibration over luminaire lifetime, at minimal cost?

Back to Table of Contents

Integrated controls. When multiple components of a lighting system are integrated into a single package at the factory, this lowers the cost of installation.

Existing research: Research ongoing at manufacturers Ams AG (ams.com/eng), Cree (lighting.cree.com), LG (www.lglightingus.com), Enlighted (www.enlightedinc.com), Orama (www.oramainc.com), Organic Response (organicresponse.com), and Philips (www.usa.lighting.philips.com).

Key research questions:

1. How best can sensor/control/communication/performance-metering packages be integrated in luminaires at low unit cost with high value added?
2. How best can new sensors or communication modules be added in the future to existing luminaires, perhaps through a peripheral bus standard?

Interoperability. When a lighting system product line, designed for a 10+ year lifetime, is discontinued 2 years after purchase, how can the system be maintained and augmented for the next 8+ years? When many hardware vendors share a small nascent market, how can application developers achieve a critical mass of users?

Existing research: None identified.

Key research questions:

1. How best can open standards support a combination of future extensibility & backwards compatibility (multi-generational interoperability)?
2. How best can open standard test compliance ensure multi-vendor product interoperability?
3. How best can open standards support development of third party applications?
4. How best can open APIs support third party application development?