4E Energy Efficient End-Use Equipment
International Energy Agency

System-level Energy Efficiency Policy Modelling and Monitoring

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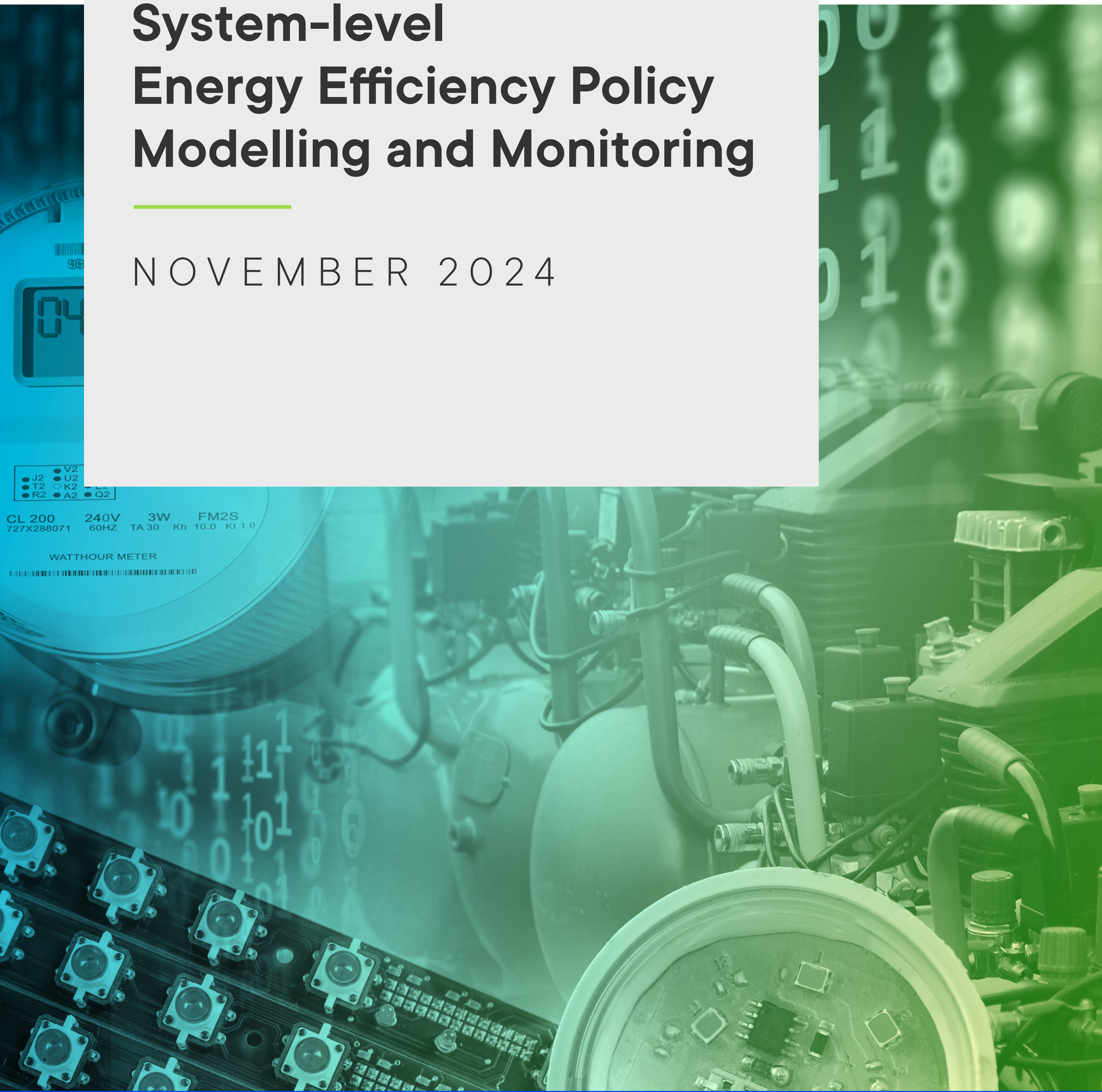

Technology Collaboration Programme
by iea

About 4E

The Technology Collaboration Programme on Energy Efficient End-Use Equipment (4E TCP), has been supporting governments to co-ordinate effective energy efficiency policies since 2008.

Fourteen countries and one region have joined together under the 4E TCP platform to exchange technical and policy information focused on increasing the production and trade in efficient end-use equipment. However, the 4E TCP is more than a forum for sharing information: it pools resources and expertise on a wide range of projects designed to meet the policy needs of participating governments. Members of 4E find this an efficient use of scarce funds, which results in outcomes that are far more comprehensive and authoritative than can be achieved by individual jurisdictions.

The 4E TCP is established under the auspices of the International Energy Agency (IEA) as a functionally and legally autonomous body.

Current members of 4E TCP are: Australia, Austria, Canada, China, Denmark, European Commission, France, Japan, Korea, Netherlands, New Zealand, Switzerland, Sweden, United Kingdom and the United States.

Further information on the 4E TCP is available from: www.iea-4e.org

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Disclaimer

Executive Summary

Introduction

This report, commissioned by the Energy Efficient End-Use Equipment Technology Collaboration Programme (4E), explores opportunities to improve the energy efficiency of systems through the use of modelling and monitoring in regulations. 4E defines a system as “a functional unit that consists of two or more physical parts that need to be assembled at the location where the system is used”. The energy savings potential for common systems like street lighting, pumps, and commercial cooling is estimated at 4 780 TWh per year, but many are not yet effectively regulated.

Regulating the energy efficiency of systems is challenging because they are often custom designed and installed in-situ, making testing complex and resource intensive. Two complementary solutions to these barriers are explored in this report: 1) Modelling the system to demonstrate it will meet the desired performance standards, and 2) Using digital sensors and monitoring to verify performance.

Methodology

The work is split into two parts. Part 1 examines existing applications of system modelling and monitoring in regulations and other policies in 4E countries to identify common aspects, approaches and solutions. Part 2 applies the learnings to two case study systems: lighting systems and compressed air systems.

The research methodology involved literature searches of potential example system regulations in areas such as building codes, safety monitoring, vehicle emissions, and voluntary certification schemes. When modelling or monitoring aspects were identified, the technical requirements and implementation methods were documented. Findings that could inform approaches for the case study systems were highlighted.

Existing Examples of Modelling and Monitoring

The research found very few examples of modelling being required in energy efficiency regulations. Some regulations allow the use of models, for example building energy models are commonly used to meet building code requirements; lighting models are sometimes used within building regulations. However, the validation procedures for these models are not yet fully robust.

Similarly, mandatory monitoring has been proposed in only one draft energy efficiency regulation (for heaters in the European Union) and this is intended for consumer information, not for checking regulatory compliance. However, examples of monitoring required by regulation were found in other policy areas including:

- Structural Health Monitoring of buildings in China uses sensors to continuously monitor key parameters and compare them against expected values from design models.
- Vehicle emissions monitoring in the European Union and the United States uses On Board Diagnostics to monitor equipment performance and issue alerts if malfunctions could increase emissions.
- Utility energy savings programs for lighting controls require pre- and post-retrofit metering of operating hours and energy consumption.

Voluntary monitoring is also used in areas like home security, where standards specify requirements for alarm transmission, and Internet of Things devices, where standards address cybersecurity.

Key findings that could be applied to energy systems include:

- Developing standardised reporting formats for model inputs and outputs and monitoring data.
- Certifying models as fit for purpose. Ideally models should be validated.

- Components need to be tested and certified. Preferably information on components is available in a publicly available database and/or embedded in models.
- Requiring systems to be registered so monitoring and reporting can be enforced.
- Establishing testing, maintenance and security guidelines for monitoring systems.
- Training and certifying individuals to verify model results and conduct acceptance testing.
- Using monitoring data to check model accuracy and optimise performance over time.
- Combining prescriptive requirements, commissioning checks and monitoring to verify savings

Case Study 1: Lighting Systems

Lighting system regulations to date have tended to set simple requirements for lighting levels and maximum power density. Some require basic controls like occupancy sensors and daylighting, but without detailed commissioning. This means the full savings potential from advanced controls (as much as 50%) is often not realised.

Sophisticated lighting models exist and are sometimes used to demonstrate compliance with building codes, but the validation procedures have limitations. Monitoring of lighting operating hours and power is used in utility incentive programs but has not been required by regulations. Recent lab testing showed some lighting control systems can accurately self-report energy use, demonstrating the potential for monitoring-based regulations.

The report proposes a two-pronged approach:

1. In the near-term, adopt elements of the latest California Energy Code, which specifies mandatory controls with functional requirements, robust design documentation, and certified acceptance testing. This pragmatic approach maximises savings without requiring fully validated models or sensor standards.
2. In the longer-term, use a combination of certified models to check designs meet requirements, acceptance testing to verify installation matches the design, and continuous self-reporting of energy use to confirm ongoing performance.

Work is needed to improve model validation methods, develop sensor standards, certify acceptance testers, and establish protocols for certifying lighting systems for energy monitoring. An overall policy framework should include product databases, standardised performance reporting, and protocols for identifying and addressing non-compliance.

Case Study 2: Compressed Air Systems

Compressed air system efficiency depends on complex interactions between air compressors, treatment equipment, distribution system design, controls, and end uses. Very few regulations exist, with the California Energy Code again being the most advanced in requiring efficient compressor and piping design, leak testing, acceptance testing and monitoring. Audits using temporary metering are the main efficiency intervention elsewhere.

Accurate, complete compressed air system models do not yet exist, though some progress has been made on subsystem models. Compressor performance standards and a common but voluntary reporting format in the US provide a foundation to build on.

The report recommends extending the California Energy Code requirements for compressed air to other jurisdictions as a near-term step, adding certification of acceptance testers. Longer-term recommendations include:

- Developing a standardised reporting format and database for compressor performance data.
- Creating and validating subsystem models for compressor packages and distribution systems.
- Requiring key components to have integrated sensors where feasible.
- Estimating peak and dynamic airflow in the design phase and verifying with monitoring.
- Metering airflow and pressure before any system upgrade to establish a baseline.

As with lighting, an overarching policy framework should be established to maximise impact. Key components include mandatory registration, model and sensor accuracy requirements, inspection powers, and non-compliance protocols.

Conclusion

Realising the large yet largely untapped potential for energy savings in systems will require innovative approaches. The current work finds that while modelling and monitoring are not yet independently robust enough to regulate efficiency in lighting and compressed air systems, a smart combination of prescriptive requirements, certified models, acceptance testing, and continuous monitoring has strong potential.

Foundational elements like test methods, accurate models, databases of parts performance, reporting standards, and a policy framework to enable the approach will need to be developed through further research, stakeholder engagement and policy design. By strategically advancing these building blocks, policymakers and energy efficiency proponents can expand the horizons of product policy and drive major reductions in energy use and emissions from these critical end-use systems.

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Glossary

AWEF	Annual Walk-in Energy Factor - parameter used in US MEPS for walk in cold rooms
BIM	Building Information Modelling
BMS	Building Management System
BREEAM	Building Research Establishment Environmental Assessment Method
CAS	Compressed Air System
CFD	Computational Fluid Dynamics
components	Identifiable items that can be purchased and assembled together to make a system. Any sub-components of the components are excluded
Cold room	Walk in cold room as distinguished from cold stores, which are stand-alone
EU	European Union
EUI	Energy Usage Intensity
IEA	International Energy Agency
IEA 4E	IEA Energy Efficient End-use Equipment. An IEA Technology Collaboration
IoT	Internet of Things - the interconnection via the internet of computing devices embedded in everyday objects, enabling them to send and receive data
LEED	Leadership in Energy and Environmental Design, a green building rating system, see https://www.usgbc.org/leed
LENI	Lighting Energy Numeric Indicator
LPD	Lighting Power Density
MEPS	Minimum energy performance standard
MVE	Monitoring, verification and enforcement
MSA	Market surveillance authority
OBD	On Board Diagnostic system for vehicle emissions
OBFCM	On-Board Fuel Consumption monitoring
Point of application	The point at which the regulatory requirements apply in the life cycle of the product/system
PV	Photovoltaic
Responsible person	The person legally responsible for ensuring the requirements are fulfilled
(regulatory) requirements	The legal requirements which must be fulfilled before a product may be sold or used in a jurisdiction
SHM	Structural Health Monitoring – used to check the safety of civil infrastructure
SME	Small and medium-sized enterprise
Sub-system	A number of components which provide a specific function in the larger system (which might be effective to regulate)
TWh	Terawatt-hour

1 Introduction

The Energy Efficient End-Use Equipment Technology Collaboration Programme (4E TCP) has commissioned a number of pieces of research into the opportunity for energy efficiency policies that look beyond the traditional product level interventions to consider a system-level approach. ‘System’ is a broad concept when applied to energy efficiency policy, therefore 4E defines a system as:

‘a functional unit that consists of two or more physical parts that need to be assembled at the location where the system is used’.

Where:

- The **functional unit** draws a boundary between the system and the environment or other systems.
- A **part** is a single, identifiable piece that contributes to the function of the system and which needs to be assembled at the location. For example, a hydraulic pump, an electric motor, a variable speed drive and water pipes are parts of a water pump system.
- A **system** is assembled by connecting the parts together on location and is typically undertaken by a professional actor. Systems and products must also be installed, i.e. connected to another system in the environment such as an energy grid or a piping system.

The energy savings potential for common systems (for example: street lighting, pumped systems, commercial cooling) has been estimated at 4 780 TWh a year (Wu et al 2022); however, many of these are yet to be effectively regulated.

Systems are often custom designed and then installed in-situ. They frequently interact with the environment they operate in, and are commonly retrofitted into an existing, larger system, rather than installed as a complete, new system. This makes testing their performance complex and much more resource intensive than testing a single (representative) unit of a (mass-produced) product with well-defined test standards in a test lab.

As a result, the ability to develop and enforce energy efficiency policy for systems is limited; it is difficult to set the performance standards required, check that a designed system meets this requirement and verify that the installed system meets the claimed performance. These constraints were investigated in a previous project (Wu et al 2022). The goal of this study is to explore two complementary solutions to the barriers posed by regulating the energy efficiency of a system:

1) Modelling the system to demonstrate that the system will meet the desired performance standards.
2) Digital sensors and monitoring.

The work is split into two parts. In Part 1, we researched existing applications of system modelling and monitoring in 4E countries. This was to identify how extensively they are used, common aspects, approaches and solutions, that inform the second part of the project, applying modelling and monitoring to two case study systems: lighting systems and compressed air systems.

2 Methodology

2.1 Identifying examples of regulations and other policies with modelling or monitoring aspects

The following areas of regulation were investigated as they were known to, or have potential to involve modelling or monitoring:

- Existing and proposed Minimum Energy Performance Standards - MEPS or labels for energy systems
- Existing and proposed MEPS or labels that incorporate monitoring or modelling
- Building regulations for energy systems - Lighting systems
- Building regulations for energy systems - Other energy uses
- Building certification schemes such as LEED and BEAMA
- Safety regulations for critical civil infrastructure – Structural Health Monitoring
- Vehicle emission regulations that incorporate monitoring or modelling
- Street lighting (intelligent systems)
- Smart products (heat pumps, air conditioners, thermostats).

In addition, regulations beyond energy use were considered as there was the potential for learning that could be transferred from these to energy efficiency.

A literature search of each of these potential example system regulations was carried out to identify the extent of modelling or monitoring included in the regulations.

When modelling or monitoring aspects were identified, the aim was to describe the technical requirements of the modelling and monitoring, and how these requirements are applied to achieve the stated goals. This includes:

- The complexity of modelling, ranging from simple calculations to digital twins.
- The way external factors and non-tested parts of the systems are addressed.
- The types of monitoring and reporting e.g., spot checks to real-time.
- Resource/input requirements for modelling or monitoring.
- The goals of the modelling and monitoring e.g. estimating/verifying/optimising performance, predictive maintenance.
- The way the regulations/policies implement the modelling and/or monitoring and any shortcomings.

This search was undertaken using key word searches of the white literature (papers in journals) via Google Scholar and grey literature (conference papers, technical reports, guidebooks etc) and general searches using internet search engines. This was supplemented by previous experience of the authors from other projects on systems.

2.2 Selection of case studies

Research was focused on existing standards for components or parts of systems, on existing approaches to regulating systems and research on modelling and monitoring systems. The approach taken was multi-stranded and iterative: work on lighting systems and compressed air systems (CAS) suggested additions to existing approaches and vice versa.

Existing regulations for lighting systems are all parts of building regulations: The three examples described below are indicative of their use in 4E, for exploring the different facets in these regulations, and identifying the aspects that deliver the most complete regulation of energy use in lighting systems. The example building regulations are all in English – it is possible that regulations in the languages of other 4E countries, for example, Japanese or Chinese, would provide other insights.

Compressed air systems appear to be rarely regulated; only the (United States) California Energy Commission regulations were identified. Auditing and manufacturer advice is the more common approach to improving efficiency of CAS. These options were investigated to identify if and in what ways the modelling and monitoring could be adapted or provided ideas for possible CAS system energy use regulation.

3 Example policies in 4E countries

3.1 Examples investigated and found not to be relevant

Some systems were identified as possible examples but found not to be relevant. These are described briefly for completeness in this section.

3.1.1 Intelligent street lighting

Intelligent street lighting uses monitoring of conditions – such as ambient light levels and road usage – as inputs to controls for lighting levels. It was thought that some regulations, or procurement guidelines, might specify how monitoring should be used. However, no examples of this were found. For example, the EU green public procurement criteria for road lighting and traffic signals (European Commission 2018a) encourages the use of dimming controls but does not require monitoring of light levels.

3.1.2 US MEPS for split air conditioners

In the past the US Energy Conservation Standards (MEPS) and associated test standard for split air conditioners (a subset of central air conditioners) allowed the use of a model to match suitable indoor and outdoor units, and to calculate the efficiency of the resulting system. The current test standards (US Department of Energy 2017) require manufacturers to test a model of the outdoor unit with a model of the indoor unit. This change was in the latest version of the regulation which took effect on 1 January 2023.

3.2 Existing and proposed MEPS or labels for energy systems

3.2.1 Proposed EU solar PV systems label

The final report of the ecodesign and energy labelling preparatory study on Solar Photovoltaics (Solar PV) was published in December 2020 (Dodd et al 2020). One of the two proposals for an energy label was for a residential/rooftop (peak power less than or equal to 20 kW) solar PV system.

The preparatory study considered two approaches for an energy label:

- A simplified package approach, based on component efficiency, with the package provider taking responsibility for calculating the Energy Efficiency Index (EEI) and the resulting label.
- A systems approach, where the product performance reflects site conditions, with the installer taking the responsibility for calculations and the resulting label.

The preparatory study recommended a system label, with the system-based Energy Efficiency Index[1] (EEI) expressed in units of $MWh/kWp.m^2$. The preparatory study researchers developed a transitional method (a spreadsheet) to calculate the EEI, which would have been made freely available if the proposal had been

[1] The parameter used in all EU energy label regulations.

adopted in the regulation. This method required data on the performance of the system components and the situation of the system (solar climate; shadowing, orientation, and inclination of the solar panel). The intention was that the system efficiency calculation and the energy label would be the responsibility of the installer of the PV system. The approach was subsequently described in an article by Polverini et al (2021).

In response to the development of ecodesign, energy label and Green Public Procurement criteria representatives of the photovoltaic value chain came together to set up a Joint Mission Group (JMG) under the umbrella of the European Technology Innovation Platform Photovoltaics (ETIP PV) - in cooperation with SolarPower Europe, PVThin, the European Solar Manufacturing Council, and IECRE - to review the results of the ecodesign and energy labelling preparatory study and provide recommendations for next regulatory discussions. The JMG published their responses, including in Wade et al (2021). The JMG were concerned that the energy label as proposed was too narrow in scope and suggested replacing this by a more holistic evaluation of sustainability performance which they termed the Environmental Impact Index.

Ecodesign and energy label regulations for solar PV have not yet been adopted as of January 2024. However, it is understood that there is not intended to be a PV system label.

3.2.2 System-like approach for US walk-in coolers and freezers MEPS

The US energy conservation standards (MEPS) for walk-in coolers and freezer (abbreviated to WICR for Walk in Cold Rooms) takes a pseudo system approach to standards: performance requirements are set for each component of the WICR (walls, doors, glazing, lights, chillers) and, in addition, a minimum value is set for the Annual Walk-in Energy Factor (AWEF). The AWEF is the ratio of the total heat removed from a walk-in box during one year period of usage for refrigeration (not including the heat generated by the operation of refrigeration systems), to the total energy input of the refrigeration systems during the same period (US DoE 2023).

The AWEF of the refrigeration system is similar to the more familiar SEER calculation for air conditioners. It calculates the overall efficiency by assuming operation at different load levels for different periods of time. Specific calculations are provided for each system variation (i.e. fixed vs variable speed, indoor vs outdoor condenser unit, matched vs unmatched condenser and evaporator). It is assumed that the refrigeration runs at a steady state of 70% system capacity during peak hours (8 hours per day) and 10% off peak (16 hours per day) (80%/40% for freezers). The test standard for AWEF is the AHRI Standard 1250–2020 “Standard for Performance Rating of Walk-in Coolers and Freezers”.

Thus, the MEPS does not include monitoring or modelling and is not a relevant example.

3.3 Monitoring or modelling in existing or proposed MEPS or labels

3.3.1 Proposed EU space and combination heater requirement for self-monitoring in draft ecodesign regulation

EU ecodesign regulations set MEPS for energy related products (as well as requirements on material resource efficiency such as repairability). The draft regulation for space and combination heaters (combination of space and water heaters) issued in March 2023 (European Commission 2023a) includes a requirement[2] that the heater determines, stores and makes visible either on the heater or on remote devices such as dedicated displays, websites, smartphones, the instantaneous and cumulative data on:

- Energy input (electricity, gaseous or liquid fuels)
- Thermal energy output
- Energy efficiency (heat output/energy input)
- Number of on/off cycles (periods with no input) and
- For combination heaters whether the heater is used for space heating or sanitary water heating.

[2] in ANNEX II Ecodesign requirements point 7

The data shall be available and accessible only to the final consumer, unless the final consumer shares and/or gives permission to access (part of) these data to third-parties such as installers, manufacturers, and public authorities (In line with the EU General Data Protection Regulation (EU) 2016/679) which protects personal data).

The draft regulation for space and combination heaters (as of March 2024) has yet to be finalised so it is not known if this requirement will be adopted. If it is adopted, this will be the first EU MEPS where the product is required to provide a report of energy use, including energy efficiency. This would set a precedent for one aspect which could be helpful for regulating energy systems, namely requiring the system to report to the user selected key parameters including energy efficiency.

3.4 Exploring the use of lighting models in regulations

The authors found no evidence of lighting regulations which require the use of lighting models; however, many regulations allow the use of models. Therefore, the models and their validation are discussed in this section.

3.4.1 Use of lighting models

There are many lighting models which use advanced modelling techniques. Raytracing and/or photon mapping are also used to calculate the illumination level, and are more accurate for more complex designs, such as buildings with glass walls and large atria. Raytracing lighting simulation programs like RADIANCE allow users to simulate almost any lighting situation with extraordinary accuracy and photographic image quality. The RADIANCE[3] simulation engine has been incorporated into various other lighting design tools (e.g., DaySim, Ladybug/Honeybee, Groundhog, DIALux , Fener, IES-VE, DIVA-for-Rhino, LightStanza, OpenStudio), Gentile et al (2021a). Some models, for example DIALux[4], include an extensive catalogue of lights. This means that the user does not need to enter the parameters of the lights – they can select them from the catalogue, which saves time and increases accuracy. DIALux also includes the ISO standard adjustment factors for regulatory compliance. Geisler-Moroder (2019) provides a review of twelve sets of software used for modelling against criteria such as type of interface, algorithms/engines used and how they address control systems.

Models are reported as increasing in speed and capability. For example Gentile et al (2021a) state that: *"To … support dynamic assessment of daylighting performance over a whole year or in parts, further simulation tools have been developed, which support the evaluation of climate-based daylight metrics, while also evaluating the thermal behaviour of fenestration elements; thus performing a holistic evaluation of visual conditions, thermal comfort and energy performance. Combined use of raytracing and matrix algebraic algorithms has increased the speed of annual daylight simulations by several orders of magnitude with near comparable levels of accuracy to conventional raytracing-based simulations".*

Game engines are also used. These are physics and game simulations that underlie modern, highly realistic computer games. These are used to visualise the system, e.g. present it to clients and allow them to walk through the room as if in a computer game (Scorpio et al 2022). These produce visually highly realistic results but have no energy modelling.

3.4.2 Validation of lighting models

There have been numerous studies focusing on the accuracy of the RADIANCE model, which underlies most of the other lighting models. For example, Jones and Reinhart (2015) tested the performance of two variations of the model in a room with no daylight and one daylight room, measuring light with high dynamic range cameras. The (two variations of the model) *"allow for the possibility of 20% error in daylight simulation results when applying them to energy calculations."*

[3] https://www.radiance-online.org/, free access
[4] https://www.dialux.com/, free access

There is a standard for validating lighting models: CIE 171 (2006)[5]: 'Test Cases for Assessment of Accuracy of Lighting Computer Programs' Scope. This standard uses a validation approach based on the concept of separately testing the different aspects of light propagation against a suite of test cases. Two types of reference data are used: data based on analytical calculation (for cases including daylight) and data based on experimental measurements (for artificial lighting). The analytical test cases are thus validated against another lighting model.

Many lighting models have been validated using CIE 171 including:

- RADIANCE (Geisler-Moroder 2010)
- APOLUX and LightTool (Moraes et al 2013)
- DIALux (Mangkuto 2016)
- NVIDIA® Iray (Dau Design and Consulting 2016)
- Relux Desktop 2019 (Bouroussis et al 2019).

However, two of these studies (Mangkuto 2016, Dau Design and Consulting, 2016) have identified errors and issues with CIE 171. Further a blog by Ashdown (2016) calls for two broad changes in the standard and changes in six of the analytical case studies to make validation more robust.

Based on the literature reviewed it appears that, while an existing standard to validate lighting models exists (CIE 171), there are issues and concerns with using it. A major concern is the use of one model to validate others for the analytical cases (involving daylight). Therefore, it would be preferable for these issues to be addressed before an energy efficiency regulation required the use of validated lighting models in demonstrating compliance of lighting systems.

At least one example of a DIALux simulation being compared with measured data is documented; Wiśniewski (2020) compared the measured and modelled illuminance and power of a lighting scheme for a reception area. The results showed that average illuminance agreed well in full power or reduced power (reduced lighting out of working hours) and installed power at full power also agreed well. However, the DIALux simulation overestimated the power in the reduced power setting by a factor of two.

3.5 Building modelling and monitoring in voluntary certification schemes

3.5.1 Certification and modelling

There are many voluntary certification schemes for the energy or environmental performance of buildings. Most are national such as Australian NABERS and US ENERGY STAR®. Others are international; two of the most widely used of these are LEED (Leadership in the Energy and Environmental Design) developed by the US Green Building Council and BREEAM (Building Research Establishment Environmental Assessment Method). Both schemes take a similar approach to assessing energy performance, to each other and to that of most building regulations –termed by BREEAM as the "national calculation method". This approach compares the performance of the proposed design to that of a base case building. The proposed building is granted credits for performance improvement over the base case building.

The authors did not find in literature that any building certification scheme require the use of energy models[6]. However it is recognised that models are widely used in the certification process, with advantages including (Schwartz & Raslan, 2013):

- *"...The improvement of the environmental performance of buildings through the provision of an effective mechanism for optimizing internal environmental conditions."*

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[5] https://cie.co.at/publications/test-cases-assess-accuracy-lighting-computer-programs

[6] For example using a model is one option for LEED Minimum building energy performance Green Infrastructure and Buildings v4 (https://www.usgbc.org/credits/neighborhood-development-plan-neighborhood-development/v4-draft/gibp-1) with others including complying with ASHRAE 50% Advanced Energy Design Guide.

- *"…The facilitation of the application of a holistic approach to assessing the overall performance of design proposals."*

As reported in Schwartz & Raslan (2013) in 2011 BREEAM required models to be accredited by the appropriate body/procedure for implementing the national calculation method. This is affirmed in the most recent Technical Manual for UK new construction (BREEAM 2023) (this also includes a non-exhaustive list of programs with advanced capabilities for designing HVAC systems and controls).

Schwartz & Raslan (2013) carried out a comparative analysis of three widely used models using a single case-study building and then compared, for each model, the energy results and the ratings under two certification schemes: LEED and BREEAM. They found that the three models (Tas-EDSL, EnergyPlus and IES-VE) provided very different values for energy use (up to 60%), although all predicted greater energy use in the baseline building compared to the designed building. When the energy values were applied in the BREEAM and LEED methodologies, despite the differences in the overall predicted energy demand generated by the various models, the performance improvement between the 'Designed' and 'Baseline' building was similar using all three models. The authors concluded that *"..this is because both BREEAM and LEED express 'performance improvement' as a ratio between the performances of the 'Designed' building against a 'Base-case' building. Assuming both buildings are "built" and simulated by the same tool using the same weather-file, the major contributors to the overall rating will be the parametric difference between the buildings (U-values, glazing ratio, system efficiencies etc.)."*

Building Information Modelling (BIM) can be described as a working methodology, which makes it possible to manage the project's 3D-model and data in a digital format during the building's life cycle. BIM-based energy modelling uses the design BIM to create the input file for the energy modelling software, using standardised data structures for information exchange. The information about the architectural design and the mechanical loads, properties, and systems that are generated by the design team and used in the design BIMs can be transferred to the energy modelling program (US GSA, 2015). However, Ryu and Park (2016) point out that it is necessary to validate the BIM using quality check programs such as Solibri Model Checker[7] and Navisworks[8]. A literature review by Carvalho et al (2020) found that researchers have used BIM to make assessments of energy related measures in BREEAM and LEED.

3.5.2 Certification and monitoring

LEED have a pilot alternative compliance path to allow an alternate performance method for documenting performance improvement of a building[9]. This method uses metered energy performance data to document the achievement of the credit intent: *"…To reduce the environmental and economic harms of excessive energy use by achieving a minimum level of energy efficiency for the building and its systems"* (LEED 2019). This is open to all Building Design and Construction, Interior Design and Construction and Homes Midrise projects that meet eligibility requirements (sufficient metering and occupancy). A licensed professional must verify the building metered data.

The authors found no evidence on how widely the pilot had been used, and whether the pilot will be adopted into LEED certification.

3.6 Use of modelling for overall energy use in building regulations

Energy efficiency targets are widely used in building regulations. These regulations use a combination of setting MEPS for components and using building modelling to define and prove efficiency performance requirements. Due to the size of the regulations, only a summary of the regulations, all of which follow a

[7] https://www.solibri.com/solibri-office
[8] https://www.autodesk.eu/products/navisworks/features
[9] https://www.usgbc.org/credits/new-construction-core-and-shell-schools-new-construction-retail-new-construction-healthca-95?return≠pilotcredits/New-Construction/v4

similar framework, is described. Because lighting and compressed air systems are regulated under building regulations, more detailed analysis is covered in each case study.

3.6.1 Defining standard models, calculations, and MEPS

Building regulation MEPS are built on standard cases and calculations. These cases serve as benchmarks, defining what constitutes acceptable levels of energy performance for new and existing buildings. MEPS are set based on these calculations, specifying the minimum energy efficiency levels that buildings must achieve based on a building of a similar size but standard design. One of the difficulties is creating acceptably accurate models which are not too complicated to assess or implement in software solutions. It is important to consider the resources required to develop and maintain these models. As explained in Section 3.5.1 there can be very large differences in the estimated energy of a building between different models.

3.6.2 Standardised use profiles

Standardised use profiles define typical usage scenarios for buildings, which include occupancy, operational hours, and appliance use. This standardisation helps to make sure energy performance assessments are based on comparable and realistic usage patterns. However, the diversity of building uses can make this standardisation challenging, as they will not accurately reflect all specific use cases, leading to discrepancies between predicted and actual energy use.

3.6.3 Software implementation and validation

Software can replicate every input and calculation of the regulation model. Allowing software vendors to incorporate model calculations into their products facilitates flexibility and accessibility. Some 4E country building regulations require models to be validated before they can be used to meet the requirements of building regulations. To date this has been done in a limited manner. Ohlsson and Olofsson (2021) critically review the practice of validation and uncertainty analysis of building energy models. They compare this to verification and validation frameworks obtained from the field of scientific computing as applied to ship hydrodynamics and nuclear energy and nuclear weapons research. The current practice of 'validation' of building energy models is usually performed by modelling several standard buildings and checking that the results are identical. The authors consider that this should more properly be termed 'verification' – it provides evidence that the model equations are correctly solved for these specific cases, but it does not ensure that this will be true for other cases. They present a case study on the verification and validation of the European and International standard models in CEN ISO 13790 and 52016–1 for the calculation of the hourly energy use for space heating and cooling. They find that from the perspective of the benchmark verification and validation frameworks these standard models cannot be considered as validated.

3.6.3.1 Use of a standard building energy calculation procedure in the EU

The international standard "EN ISO 52016-1:2017 - Energy performance of buildings - Energy needs for heating and cooling, internal temperatures and sensible and latent heat loads - Part 1: Calculation procedures" is of particular importance in the EU, as it is referenced in the 2018 revision of the Energy Performance of Buildings Directive (EC 2018b). Specifically, *"...Member States shall describe their national calculation methodology following the national annexes of the overarching standards, namely ISO 52000-1, 52003-1, 52010-1, 52016-1, and 52018-1".*

Van Dijk (2019) describes the procedures and compares the results for three standard test cases against those for nine commonly used procedures/models. He found the results from the ISO 52016-1 procedure similar to these. Several researchers have compared ISO 52016-1 against existing models for a range of cases, as reported in De Luca et al (2021). In all examples they have found significant discrepancies.

3.6.3.2 The US case: standard to evaluate building energy models - ASHRAE 140

The standard for model validation associated with the US building standard ASHRAE 90.1 is ASHRAE 140

"Standard Method of Test for the Evaluation of Building Energy Analysis Computer Programs". As reported by Muehleisen (2023), there were several shortcomings to ASHRAE 140 which include:

- Test suites focused more on diagnosing software algorithm differences than establishing criteria for software accuracy.
- No empirical validation test suite i.e., no "ground truth to measurement".
- Creating 140 models, extracting out results, and putting them in reporting spreadsheets was extremely manually intensive.
- The 140 test cases are dramatically simpler than typical designs modelled in 90.1 Performance Rating Method.
- Many common systems and components in 90.1 designs are not in the 140 test cases.
- There are no pass/fail criteria, only comparison results between selected software.

In response the US Department of Energy (DOE) have funded and continues to fund work on maintenance and development of ASHRAE Standard 140. Progress has included publishing acceptance criteria for some test suites, adding new test suites and developing workflows to help vendors perform[10] and submit ASHRAE 140 testing automatically. In addition, other DOE projects are completing experiments and analysis designed specifically for empirical validation or "ground truth" testing in ASHRAE 140.

In previous work for DOE Karpman et al (2022) identified gaps between systems and components covered by the current Standard 140 diagnostic unit test[11] cases compared to the design elements common in the 90.1 Performance Rating Method models viewed. They found that there was no diagnostic unit test for daylighting controls in ASHRAE 140. They considered that it should be a high priority to add this as lighting is one of the major energy uses. They proposed that the tests should include sensitivity to fenestration area, visible transmittance, shading and orientation of the vertical fenestration and skylights, required illuminance, and type of daylighting controls (e.g., stepped control vs. continuous dimming).

3.6.3.3 Summary of building energy models and their use in building regulations

The evidence we have found suggests that some of the standards for calculation procedures used in building regulations (EN ISO 52016-1) and for validation of building energy models (ASHRAE 140) have significant failings. Lighting energy systems have some similarities with building energy models but are arguably less complex – as discussed above the most widely used model has been validated to some extent. However, developing robust model validation will require considerable resources. Compressed air systems differ considerably from buildings, so it is more difficult to draw lessons from the experience of the latter from the former.

3.6.4 Alternative models and software

Regulations may also allow the use of alternative calculations and models. This promotes innovation and can accommodate models for more unusual building designs. However, it requires more rigorous software validation processes to be defined.

3.6.5 Training and certifying model users

Training and certifying individuals who use these models is another critical component of this approach. This ensures that the professionals responsible for calculating and evaluating building energy performance are competent and can reliably apply the models and standards. Certification can also provide more accountability or insurance against user mistakes. While this enhances the integrity of the energy performance assessment process, it also requires ongoing education and certification programs, which

[10] https://www.energy.gov/eere/buildings/ashrae-standard-140-maintenance-and-development#:~:text=ASHRAE%20Standard%20140%20%E2%80%9CStandard%20Method,current%20generation%20of%20BEM%20software

[11] diagnostic unit tests focus on the capabilities of the building performance model software with respect to individual building systems and components, to help identify the impactful parameters and verify the related software algorithms.

can be resource-intensive. For model users there must be a reasonable expectation of sufficient work to undertake the training.

3.6.6 Compliance checks

Compliance checks at various stages of a building's life cycle, including design, construction, and commissioning, ensure that energy efficiency targets are integrated from the outset and maintained throughout. This multi-stage approach helps identify and rectify issues early, though it also introduces complexity and potential delays in the building construction process. Compliance checks do not include the overall efficiency of the building, but can cover critical aspects such as air tightness testing and infrared imaging to identify thermal bridging.

3.6.7 Connection of models to monitoring data

Although current building regulations do not mandate ongoing monitoring or compliance with modelling post-construction, there are early steps towards integrating models with real-time data, such as through EnergyPlus[12]. This integration could bridge the gap between predicted and actual energy performance, allowing for continuous improvement.

3.6.8 Summary

Buildings are significantly more complex systems, more numerous and the combined energy use is higher than the case-study systems (lighting and CASs) considered in this work. It may not be practical to set as demanding requirements for the case study systems.

The accuracy of models in building regulations are still restricted by the use of standardised profiles/cases which are unlikely to match real performance. To date building regulations do not utilise monitoring, which could provide an alternative to some of the steps required. Even with monitoring, some compliance checking is needed if the costs for rectification are high. In addition, any monitoring depends on the sensors accurately measuring the intended variables, which can only be verified by checking that the sensors have been correctly installed.

3.7 Structural Health Monitoring for safety of civil infrastructure

3.7.1 Introduction

"..Civil structures have an important characteristic that differentiates them from other industrial products. Each structure is unique from others. They are designed according to different local geographical and geological conditions and are built from different construction materials using different construction technologies. None of the civil structures are exactly the same; they are very different from mass-produced goods."(Fujino et al 2019). In this respect they have similarities to the case study energy systems.

The safety of some types of civic infrastructure such as bridges, tunnels, dams and high-rise buildings is of great concern because of the scope for loss of life if they fail. This applies in any situation but particularly in areas where there is a substantial earthquake risk or exceptionally high winds. This has led to the development of systems to continuously monitor the structure of the building – generally termed Structural Health Monitoring (SHM). In the United Kingdom, the SHM of dams has been mandatory since the collapse of a 30 m embankment dam that caused the death of 254 people near Sheffield in 1864. The most recent version of the legislation is the Reservoir Act of 1975 (Brownjohn, 2007). However this requires periodic checks by qualified inspectors, which is not the same as continuous monitoring using sensors, as investigated for this study.

There are codes and standards for SHM using continuous monitoring in many 4E countries. For example, Allaix and Bigaj-van Vliet (2023) review the current state of standardization on monitoring, data-informed

[12] One of the building energy simulation programs that is widely used to calculate building energy use.

safety assessment and maintenance policies of bridges and tunnels in European countries. To date most SHM has been for research or voluntary. One 4E country has made SHM mandatory in certain applications and have more direct relevance for systems regulations. This is described in the next section.

3.7.2 Chinese Technical code for monitoring of building and bridge structures

The Chinese code GB 50982-2014 appears to have been one of the first true SHM code adopted in a 4E country. San Francisco, California USA adopted a requirement to install SHM in 2013 (San Francisco 2013), but this requires data to be collected from instruments only after an earthquake has occurred, not in a continuous manner.

The text for GB 50982-2014 is not freely accessible in English – the description for this study is based on two papers: Moreu et al (2018) and Yang et al (2017). The first paper focuses on the requirements for bridges, the latter describes the code and three case studies of structures which have been monitored using this code.

Under the code sensors are required to monitor (for bridges):

- Vehicle load
- Weather and atmospheric conditions (wind speed and direction, atmospheric pressure, air and structural surface temperature, humidity)
- Global structural response (using accelerometers)
- Local structural response (using strain sensors).

The range and accuracy of each set of sensors is specified in the code. Embedded sensors are required to have durability of at least 20 years; non-embedded sensors at least 5 years. The location of the sensors is also specified in the code. The code also sets requirements for data collection (i.e. signal size, sampling frequency and synchronisation), transmission, processing and management. Neither of the two references specifies how frequently the reported data is required to be checked against the 'expected' values calculated from the design models. It may be that the SHM system is required to issue an alert if the measurements suggest that there may be damage to the structure.

These papers imply that the code requires simulation models of the structures to be developed during design, used during construction and once complete.

The code specifies two levels of safety evaluation for bridges:

- The first level, where the eigenvalues[13] of the structure are calculated using the monitoring data and compared with pre-determined values.
  - If the local structural response appears to be abnormal then further checks are done. If these checks detect bridge damage, then a second-level safety evaluation is undertaken.
  - If the global structural response appears to be abnormal then a second-level safety evaluation is undertaken.
- In the second-level safety evaluation the structural finite element model, monitored load and design load are used for structural re-analysis, calculating the ultimate bearing capacity and evaluating the bridge structural safety state and estimated reserve.

3.7.3 Insights from the use of SHM for energy system regulations

SHM as applied using Chinese code GB 50982-2014 provides a useful template for using monitoring in energy systems regulations in some respects. The code specifies:

- What needs to be monitored and how frequently.

[13] Eigenvalues are the special set of scalar values that is associated with the set of linear equations most probably in the matrix equations

- That measurements should be compared against those predicted by a model (although it isn't clear in the references found how detailed the model is).
- The procedure in case the sensors detect deviation from the expected values, with different levels of response.

All these considerations could be transferred to energy efficiency regulation for systems. There are differences which could present a challenge in relation to energy system regulation:

- Large structures require consent and need to meet other specifications besides SHM. Relevant authorities will be aware and involved in their development from an early stage; this is less likely to be the case for lighting or CA systems, particularly when they are adaptations or replacements of existing systems.
- Large civil infrastructure is likely to be required to be modelled (for structural integrity reasons) separately to the requirements under the SHM code. This may not be the case for energy systems, where developing a model could be an additional requirement on the owner/developer of the energy system.
- The consequences of a large structure failing are more severe than for an energy system using more energy than allowed, so the motivation for complying with SHM regulations is greater.

3.8 Vehicle emissions monitoring

A known use of large-scale monitoring in regulation is vehicle emissions monitoring. Its use and the possible transferability to energy system regulation are explored in this section.

3.8.1 Introduction

Two basic types of vehicle emissions are regulated, both of which include monitoring in different ways, with the means evolving over time. They are:

- harmful pollutant emissions monitoring (NO_X (Nitrogen Oxides), Particulate Matter (PM), Particle Number (PN), Hydrocarbons (HC)) using:
  - on board diagnostics
  - on board monitoring
- Energy performance (CO_2 emission) monitoring.

Regulations restricting emissions of harmful pollutants from vehicles have been in place for decades in many 4E countries. More recently regulations on CO_2 emissions have been added. This analysis focuses on the regulations in the US and the EU as they appear to be representative of the regulations elsewhere and information on them was readily available in English. Similar (and often aligned) regulations are also in place in all the other 4E countries: Australia, Canada, China, Japan, New Zealand, South Korea, Switzerland and the United Kingdom.

In the US and EU Periodic Test Inspections (PTI) or roadworthiness tests are required, generally annually, at which pollutant and CO_2 emissions are checked. Vehicles are required to have emissions below the statutory requirements in order to be allowed to operate. These inspections also check the performance of the continuous monitoring systems which are described below, therefore form part of this monitoring infrastructure. Further, in the EU the onboard data on CO_2 emissions are recorded by each Member State and the collated data sent to the European Commission[14].

In all cases the regulations include a requirement for the manufacturers to 'type test' the vehicles, that is, test a minimum number of vehicles of each model in the lab and on the road to prove that their emissions are below the limits. The objective of a post-sale in-use compliance program is to ensure that emissions

[14] EU regulation 2021/392 on the monitoring and reporting of data relating to CO_2 emissions from passenger cars and light commercial vehicles, Article 10.

stay low and continue to meet emission standards throughout the vehicles' life. As the energy systems that are the focus of this research are all customised rather than mass produced this element of the vehicle regulations is not applicable and is not considered here. As discussed in the previous report by Hansheng for 4E on systems (Wu et al 2022), one of the characteristics of some energy systems is that there is no clear cut 'supplier' – some of the systems are assembled at least in part by the owner and operator. This means that other aspects of vehicle emissions regulation:

- Vehicle suppliers are required to report the fuel performance of every vehicle they sell, so that their fleet average can be checked to meet requirements.
- Vehicle suppliers in California are obliged to provide warranties of emissions performance (if part of the emission control system of a vehicle fails within the warranty period the manufacturer has to replace or repair it at their own cost) Cackette (2016)).

are not transferable to energy systems.

One aspect that vehicles and some energy systems have in common is that the ways that they are operated and maintained can have a big effect on their performance. In the case of vehicles this operational side is largely beyond regulation, although marketing campaigns can have some effect on how vehicles are driven. Vehicle maintenance is addressed by Periodic Test Inspections or roadworthiness tests, even though there are tens or hundreds of millions of vehicles to be controlled. Energy systems are far fewer in number – one or more orders of magnitude less. Thus, it seems not impossible that regulations can be put in place that address, at least to some extent, both operation and maintenance.

3.8.2 On Board Diagnostic (OBD) systems

Most emissions regulations (including those in the EU and United States) require each vehicle to have an On-Board Diagnostic (OBD) system. This means that on-board diagnostic capabilities are incorporated into the hardware and software of a vehicle's on-board computer to monitor virtually every component that can affect emission performance. Each component is checked by a diagnostic routine to verify that it is functioning properly. If a problem or malfunction is detected, the OBD system illuminates a warning light (Malfunction Indicator Lamp) on the vehicle instrument panel to alert the driver. They are calibrated with thresholds for activation. OBDs do not measure emissions directly, they measure the performance of equipment that controls emissions.

However, Cackette (2016) describes the California OBD as follows: "The threshold for turning on the warning light is usually a 50 percent increase in emissions caused by the failure of a specific emission control part or system. A limitation of OBD is it does not detect emission increases of less than 50 percent, or larger emission increases that may occur due to accumulated deterioration of multiple emission control devices." This implies that emissions are measured directly.

The OBD also stores important information about any detected malfunction so that a repair technician can find and fix the problem. Once a malfunction has been detected a repair technician needs to repair the fault to reset the system (California Air Resources Board 2019). Vehicles cannot pass roadworthiness tests if there is an error alert.

3.8.3 On-board fuel consumption monitoring (EU)

Both the EU and US regulations set fleet average requirements for fuel consumption/CO_2 emissions for vehicle manufacturers. US and EU regulations require 'type testing' when a new model is placed on the market (as outlined above). In the EU there was a wish to assess the real-world representativeness of the CO_2 emissions and of the fuel or energy consumption determined at type-approval, as well as to prevent the growing of the gap between emissions tested in the laboratory and real-world emissions. From 2021 the European Commission started collecting real-world data from cars and vans using on-board fuel consumption monitoring (OBFCM) devices, starting with vehicles placed on the market in 2021. (The regulation mandating this, 2021/392[15], is separate to the regulation which sets the fuel consumption performance requirements, 2019/631 and amendment 2023/851.) There are two routes for data reporting (European Commission, 2023b):

1. Manufacturers are required to report, annually, data for all vehicles for which they have access to information, for a maximum period of 15 years from the date of the first reporting. Reporting is via a standard reporting format and an online platform (Reportnet 3) operated by the European Environment Agency.
2. Data is to be collected by Member States' designated bodies and establishments from the OBFCM device at the time of the roadworthiness tests, through a read-out from the OBD port using a scan-tool. Mandatory from 20 May 2023 and from the first roadworthiness test performed on a vehicle, starting with vehicles that were first registered in 2021. The data are to be collected for a maximum period of 15 years. A single data set is to be sent by Member States to the European Commission annually.

In both cases the data to be reported are the Vehicle Identification Number (VIN), Total fuel consumed (lifetime) (litres) and Total distance travelled (lifetime) (km).

Dornoff and Zacharof (2022) discuss the factors that will mean the fuel consumption recorded by the OBFCM differ from that recorded in formal verification testing. They have performed tests to quantify the effects of two of these: wheels and fuels. Based on experiments they propose combined OBFCM fuel consumption and distance accuracy requirements. (The EC regulation implies that the accuracy of recording of fuel consumption should be a whole number of litres and of distance travelled should be the whole number of kilometres.)

3.8.4 Proposed use of on-board emissions monitoring (EU)

The European Commission proposed new regulations, combining new limits for pollutants and CO_2 emission standards in November 2022[16] (European Commission 2022). These are termed 'Euro 7' standards. At the time of research (January 2024) the regulations were still in development; when they are finalised, they are expected to take effect in 2025/26. The EC proposal is to continue requirements for OMD and OBFCM, while adding On Board Monitoring (OBM) systems[17]. These are to be capable of detecting emissions at the tailpipe above the emission limits due to malfunctions, increased degradation or other situations that increase emissions. These OMB systems should be capable of communicating data on the emission behaviour of the vehicle via the OBD port, during roadworthiness test, and via a wireless link.

Müller et al (2022) discuss the challenges of putting this system into effect. These include access to robust sensors for pollutants which can be fitted to exhausts and the need for intelligent handling of occurrences and deviation to separate out the performance of equipment from the driving conditions (such as ambient temperature and trip length).

3.8.5 Possible lessons from emissions monitoring for energy system regulations

There are elements of vehicle emissions monitoring that could be transferred to some energy systems. These seem more suitable for the larger, more specialist, less widespread, CA systems, rather than lighting systems. Framed for the former they are:

- In order for the systems regulations equivalent to those for vehicles to work all compressed air systems would have to be registered. Possible ways to enforce registration could be via:
  - Mandatory large energy user audits (where these apply, for example under the EU Energy Performance of Buildings Directive)

[15] on the monitoring and reporting of data relating to CO_2 emissions from passenger cars and light commercial vehicles
[16] 2022/0365 (COD)
[17] One reference, Dornoff (2023) states OBM is "a concept already introduced in the United States and China". The report authors cannot find evidence that this has been adopted in regulations in these countries.

- Mandatory large building energy use reporting of energy reduction obligations (where these apply, for example Japan's Energy Conservation Act)
- Reporting by equipment suppliers of air compressors and other key components

- The regulations could make using an energy management system compulsory. These would be required to include standard alerts for performance factors that affect efficiency if efficiency falls too low (equivalent of a Malfunction Indicator Lamp on a vehicle). Action is required by the operator before the alert can be reset.
- All CASs could be required to report energy performance annually using standard outputs from the energy management system. The reporting could be online and possibly could be automated – a direct upload from the energy management system. The report would include the number of alert resets and if any alerts are active. If there are any active alerts when reporting or the number of alerts in a year above a certain threshold the operator would be required to provide an additional report and surveillance authorities would be entitled to investigate.
- There are likely to be factors which affect energy efficiency which may not be included in lab measurements or models of systems (analogous with the situation identified by Dornoff and Zacharof, 2022 outlined above, whereby vehicle emissions are affected by wheels and fuels). It may be possible to adopt a cross-check approach for energy systems, comparing models and testing of real systems in near lab conditions.

3.9 Monitoring and verification of energy savings from lighting controls in utility energy saving programmes

Many 4E countries have national, local or utility programmes where organisations are required or given financial incentives or support to reduce their energy use in one of several prescribed ways. Retrofitting lighting controls is a qualifying measure in some programmes. These programmes require monitoring and verification (M&V) of the energy savings which may include physical measurements, so these programmes provide examples of how monitoring is used for lighting systems.

3.9.1 Example from a utility programme - Ontario's Save on Energy

One example of a such a programme is Ontario's Save on Energy[18], operated by the Independent Electricity System Operator (Save on Energy, 2021). This sets different requirements for M&V depending on estimated participant incentives: for participant incentives greater than CAD 10 000 and equal to or less than CAD 80 000 engineering calculations are used; for large custom projects (incentive greater than CAD 80 000) measurements are required. A selection of the M&V requirements for lighting control large custom projects is within scope.

[18] https://saveonenergy.ca/About

Table 1: Selected requirements for M&V for large custom lighting control projects under Ontario's Save on Energy programme

Required Parameters	M&V Procedures
Existing system description	Inventory of lamp/ballast fixture type affected. Baseline information required for each type including fixture, lamp and ballast types, room conditions, usage area designation, operating periods (e.g. common space 24/7; tenant space lease hours), room location and counts of operating and non-operating fixtures and lamps. Spot-metering data for a baseline sample that is representative of each usage group.
Proposed system description	Retrofit information required for each lighting type relevant to project operating periods as per post-retrofit lighting controls' settings. Metering data for duration that reflects full operating profile.
Sampling	Baseline fixtures should be grouped into usage groups according to those with similar occupancy areas and/or expected operating hour schedules. At least six sample fixtures from each usage group should be subject to metering where measurements are required.
Baseline period and reporting period duration	Baseline and reporting period duration should span through a full operating cycle.
Metering requirements	for both baseline and retrofit: (1) Metering of fixture wattages: › Requires the use of RMS meter. › Continuous monitoring on a sample population within each usage group should be conducted. The readings will be averaged. › Meters used for this task will need to be calibrated. **(2)** Logging operatinghours › Continuous monitoring on a sample population within each usage group should be conducted for a minimum of one weeks or span of full operating cycle. › When seasonal variations or scheduled activity affect equipment operation, metering should be conducted during each variation period. (E.g. summer operating schedules in classrooms). › Metering period should not include vacations or holidays.

Note that this procedure does not require measurement of light levels and there is a separate requirement for retrofitting of light fittings.

3.9.2 US NREL Uniform Methods Project: Methods for Determining Energy Efficiency Savings for Specific Measures

This project (Uniform Methods Project: Methods for Determining Energy Efficiency Savings for Specific Measures) covers many different measures. The aspect relevant here is Commercial and Industrial Lighting Controls Evaluation Protocol (Chapter 3 in Carlson 2017). This guidance is broader in scope than the utility specific example above and so is more generic. The degree of measurement required depends on the savings impact for lighting controls; if at least 5% energy savings are expected the pre and post metering should be used.

The steps for verification are:

1) Conduct an on-site review for each project. Inspect a representative sample of controlled lighting fixtures and lighting controls reported by the implementer and verify that the controls are operating as reported. (See the "Sample Design" protocol for guidance on sampling.)

a. Confirm or correct reported controlled fixture types and wattages for each fixture in the sample.
b. Confirm or correct reported quantities for all controlled fixtures in the sample.
c. Confirm or correct the heating/cooling status and associated equipment for spaces in the sample.
d. Interview facility representatives to check baseline fixture control types and quantities reported for the sample. Confirmation or correction will be based on the interviews. When available, interviews are supplemented by physical evidence such as lighting controls installed on fixture types or in areas not changed by the project.

2) Update the lighting control inventory form for the sample, based on findings from the on-site review.

Measurement involves metering lighting operating hours for a representative sample of controlled fixtures selected for verification. The method sets metering requirements for different kinds of controls as shown in Table 2.

Table 2: Metering requirements by lighting control type

	Metering Recommendations		
Lighting Control Measure	**Pre-Installation**	**Post-Installation**	**Metering Type**
Lighting sweep controls/ energy management system/ time clock	yes	Yes	Event or power logger
Occupancy sensors	yes	Yes/No	Event/ event and occupancy logger
Stepped dimming (dual ballasts)	no	Yes	Event logger
Dual ballast (high/low hid)	no	Yes	Power logger
Continuous daylight dimming	no	Yes	Power logger

The guidance notes that ASHRAE recommends that lighting levels be measured for lighting control measures—particularly dimming measures—to make sure that adequate lighting levels at the work area are maintained.

Meters are deployed (or metering routines are established, if using an existing building management system (BMS)) during the verification site visit. The measurement process requires the following activities:

1) Meter operating hours for each circuit in the verification sample.
   a. If using light loggers, deploy loggers in one or more fixtures controlled by the circuit. Only one logger per last point of control is required; however, additional loggers are commonly deployed to offset logger failure or loss.
   b. If measuring amperage, install the current transformer and data logger in lighting panels for the sampled circuit. The sampling interval should be 15 minutes or less. Spot-measure amperage with lights on and off for the circuit leg with the current transformer. Record the amperage threshold for the lights-on condition.
   c. If the lighting control measure is an on/off type of control (such as occupancy sensors), an event type power logger can be used. Event power loggers record a change of state when the power is on and off and provide similar data as a change of state lighting logger. The sampling interval is irrelevant for event loggers because it captures transitions and data can be output at any interval desired.
   d. If using a BMS, establish trends for lighting on/off status for each circuit in the sample. The sampling interval should be 15 minutes or less. Check that the BMS has sufficient capacity to archive recorded data, and that the metering task will not adversely slow the BMS response time.

2) Check data logger operations. Before leaving the site, spot-check a few data loggers to confirm they are recording data as expected. Correct any deficiencies, and, if they appear systemic, redeploy the loggers. If using BMS trends, spot-check recorded data.

3) Leave metering equipment for the monitoring period, which could include pre and post periods. The protocol recommends a monitoring period capturing the full range of facility operating schedules. For facilities with constant schedules (such as office buildings, grocery stores, and retail shops), the protocol calls for metering a minimum of two weeks for pre periods and a minimum of four weeks for post periods. Facilities with variable schedules will require additional time. Facilities with seasonal schedules, such as schools, should be monitored during active periods.

4) Analyse metering data.

3.10 Smart devices and IoT monitoring

There are other uses of monitoring which are separate from energy or environmental public sector programmes – these are explored in this section.

3.10.1 Fire safety and security monitoring

A brief literature search did not find evidence of regulations which required remote monitoring of fire or security alarms. However, there are standards for alarm transmission systems; for example: EN 50518 is a European Standard that specifies the requirements and procedures for the design, installation, commissioning, and maintenance of alarm transmission systems used for the transmission of alarm signals from security systems to alarm receiving centres. The standard covers both wired and wireless alarm transmission systems and is intended to ensure that such systems are reliable, secure, and effective in transmitting alarm signals to alarm receiving centres.

EN 50518 includes requirements for the components of alarm transmission systems, such as control panels, alarm transmission equipment, and communication networks, as well as guidelines for testing, maintenance, and monitoring of these systems. The standard also provides guidance on the use of different types of signalling protocols and specifies requirements for their use.

Compliance with EN 50518 is often required by insurance companies, regulatory bodies, and other stakeholders in the security industry.

3.10.2 Internet of Things security standards

Security is a concern for IoT products, particularly those which collect and use personal information such as health statistics. This could also be an issue, at corporate rather than personal level, for data collected and transmitted by energy using systems.[19]

There are existing standards to address this issue, for example:

- IEC 60335-1 Ed. 6, Annex U: Appliances intended for remote communication through public networks and
- ETSI EN 303 645 and associated test specification ETSI TS 103 701
- In the US NIST published IR 8259 Foundational Cybersecurity Activities for IoT Device Manufacturers in 2020.

It may be advisable to reference these standards or incorporate some aspects of them if energy systems require remote monitoring/reporting.

3.10.3 Smart thermostats

Smart thermostats monitor and control the heating and cooling systems in a house. Smart thermostats

[19] From https://www.isarsoft.com/knowledge-hub/en-50518 accessed 15 Jan 2024

have the potential to save energy through sophisticated and sometimes AI driven algorithms. Controls are a very important part of system efficiency and a way to use regulation to set their functionality and effectiveness is a possible way to improve system efficiency.

The ENERGY STAR smart thermostat criteria[20] related to monitoring include:

- Collection of daily HVAC equipment run time
- Collection of hourly average temperature and equipment set points
- Ability for consumers to access information relevant to energy consumption.

Because the thermostat effectiveness in saving energy is heavily dependent on each individual use case, modelling is not used to estimate savings. Instead, the manufacturer is required to show field savings to a 95% confidence of their thermostats using A/B studies[21] or a process to be agreed with the EPA. This requires field installations in sufficient numbers to prove statistically significant savings. It is unclear how this could be applied in regulating the efficiency of energy systems.

3.11 Summary of findings from case study examples

3.11.1 Use of models in regulation or certification

We found very few examples of the use of models being **required** in regulation or certification of energy efficiency. The US MEPS for WICR is the only adopted example we found and this is very simple model and so not a useful precedent for more complex systems. A proposal to use a model for an energy system – EU PV domestic systems, was not adopted.

Some regulations allow or include the use of models. For example, the use of building energy models is commonplace in regulations and certification. Building regulations also allow the use of models for lighting systems. In both cases the models need to be tested or certified as meeting the regulations/standards required but the evidence is that the validation procedures in place are not yet fully robust.

The findings from these examples that could be carried over to modelling the case study energy systems in regulations are:

Finding	Example
If the use of a model is required or allowed, then it is good practice to make a model available free of charge	› Proposed EU PV system energy label › National building energy regulations
If a model is required or allowed, then there needs to be a way to certify models for use	› Voluntary building certifications › Building regulations
Ideally models used in regulations should be validated	› Building regulations
Even quite complex and certified building models can result in very different estimates of energy use. However, if the regulatory approach or certification involves a comparison of a standard and the specific **building the difference** (which is what is of interest) may be more robust to models' differences.	› Voluntary building certifications › Building regulations
Components need to be tested and certified.	› US WICR regulation › Lighting system regulations

[20] https://www.energystar.gov/sites/default/files/asset/document/ENERGY%20STAR%20Program%20Requirements%20for%20Connected%20Thermostats%20Version%201.0.pdf

[21] "A/B testing" is a shorthand for a simple randomised controlled experiment, in which a number of samples (e.g., A and B) of a single vector-variable are compared. These values are similar except for one variation which might affect a user's behaviour. A/B tests are widely considered the simplest form of controlled experiment, especially when they only involve two variants. However, by adding more variants to the test, its complexity grows.

Ideally information on components is available in a publicly available database and/or embedded in models.	› US WICR regulation › Lighting system regulations
Acceptance/compliance checks are needed to verify that a system is built as designed and the quality of installation is adequate.	› Building regulations

3.11.2 Use of monitoring in regulation or certification

Mandatory data monitoring has been proposed in one energy efficiency regulation (EU heater and combination regulation) but is intended for consumer information, not for checking whether the performance meets regulatory requirements. However, there are regulatory examples in other areas of regulation in 4E countries: Structural Health Monitoring (SHM) of buildings and large structures in China and vehicle emissions monitoring in the EU and US. The former requires the use of modelling and the comparison of measured parameters with those predicted by the model.

Another example of monitoring required by regulation, fuel consumption monitoring in the EU, is not used to directly check that the performance required in a regulation is being met; it is intended to give a picture of the overall market and how effective the regulation is considering the whole market. (This is considered necessary because fuel consumption measured in lab conditions is known to be different from that on the road.)

We found three cases of using monitored data to meet certification requirements:

1. for buildings in LEED. However this is a pilot approach, there are few details, and its status is unclear, so this is not included in the analysis in this section.
2. For Smart thermostats in ENERGY STAR. The monitoring and reporting of performance of a fleet of devices is required for certification. This approach may be valid for a mass-produced device but is not transferable to complex energy systems which are customised for each application.
3. For lighting systems in utility energy saving programmes. These approaches could be transferred to regulations.

The example regulations we have found require continuous monitoring. Vehicle emissions monitoring systems issue an alert if there is a problem or malfunction with a component that can affect emission performance. The result of fuel consumption monitoring is recorded and reported at annual roadworthiness tests. It is presumed that the SHM alerts the owner/operator if measured values indicate a structure is operating outside the required parameters.

The findings from these examples that could be carried over to monitoring the case study energy systems in regulations are:

Finding	Example
Regulations can use monitoring of an indirect measure of the regulated performance	› Vehicle emission OBD (monitors the performance of components that can affect emission performance rather than emissions directly) › SHM (monitors factors which can be used to calculate whether structural health has been degraded)
Monitored data may be reported when an anomaly is found or periodically or both	› Vehicle emissions OBD

Performance can be monitored after sale as a check that the system is still meeting statutory requirements, and equipment is being maintained adequately	› Vehicle emissions OBD › SHM
The person addressing a reported anomaly needs to be certified to do so	› Vehicle emissions OBD
The effectiveness of the regulation is increased by a periodic check of performance. If the system fails to meet the performance requirement the system's license to operate is withdrawn	› Vehicle emissions OBD
Continuous monitoring may be supplemented by additional periodic tests	› Vehicle emissions OBD
It may be necessary for all systems to be registered with the enforcement authority so that it can be checked that monitored results are reported	› Vehicle emissions OBD › SHM
Regulations may combine monitoring and modelling to check performance	› Vehicle emissions OBD

3.11.3 Voluntary uses of monitoring

Two examples of voluntary monitoring and reporting of performance have been found, both outside energy efficiency: home and business security and the general areas of the Internet of Things.

The findings from these examples that could be carried over to monitoring the case study energy systems in regulations are:

Finding	Example
Communications need to be standardised so that all systems use a common approach. This simplifies and reduces costs for suppliers and operators	› Security monitoring systems
Guidelines (or regulations) for testing, maintenance, and monitoring of these systems need to be robust	› Security monitoring systems
Communication systems need to protect sensitive information	› IoT security standards

3.12 Overall findings

Building regulations are the only example energy related regulations which use modelling. They offer some insights which can be applied to the case study systems.

Of the policies which require monitoring the closest to an energy related policy using monitoring is EU vehicle fuel consumption monitoring (although this is not used directly to check whether a regulation is being adhered to for a specific vehicle or fleet of vehicles, more to gather global data). Examples of monitoring in other policy areas: SHM in China and vehicle emissions monitoring in the EU and US, make direct use of continuous monitoring. They together with some voluntary initiatives can offer some pointers for how monitoring could be used in the case study systems.

It should be noted that monitoring is not effective if the sensors are not reliable and measuring the correct thing. Acceptance/compliance checks are needed to ensure that they have been fitted and are operating correctly and ideally 'health checks' should be included to guarantee that this continues to be the case.

4 Case study: lighting systems

The previous study adopted the definition from the EU preparatory study (van Tichelen et al, 2016) for lighting systems:

'a system of devices intended to deliver effective lighting to create a comfortable, functional and safe environment for human habitation, travel, work and leisure activities.'

For the purposes of this report, we limit the system to indoors with a defined application. This includes offices, atria, retail spaces etc. While domestic buildings are included in theory because they tend to be simple, small and with only one light fixture, they are not discussed.

Three different boundaries for lighting system can be defined:

- System excluding indoor space - This is the most product-like system and excludes the room/ building factors.
- System including indoor space - The lighting system including the room would consider all the physical room factors such as floor area, shape and windows.
- Integrated lighting approach - An integrated lighting approach is designed to consider how the overall building design affects the lighting and the rest of the building energy. For example, increasing the window size improves the amount of daylight available, reducing energy for lighting. However, in the summer this can create glare and excess solar gains which increase HVAC energy consumption, and in winter lose heat more rapidly than an insulated wall. An integrated approach would consider and balance all these competing factors, and the design might limit the wall to window ratio and include blinds or solar shading to mitigate excess gains.

Lighting systems spatially can also be defined at the building level, room level or smaller. The same principles would apply to all cases.

The most common approach is to define the system with the environment. This enables the impact of the room and control strategies to be considered and is more widely applicable to most situations such as lighting system changes.

4.1 System parts and interactions

Based on the boundaries described, the electric lighting system is made up of the:

1. light fixtures, provide the artificial lighting and are sometimes broken down further into light sources, control gear and fittings.
   - Control gear – converts AC to DC electricity
   - Light source – converts electricity to light
   - Fittings – control the direction and distribution of the light.
2. wiring which distributes the electricity to the light fixtures
3. room or indoor space to be illuminated
4. sensors and controls.

The energy losses occurring at each part are shown in Figure 1. The losses in the wiring due to electrical resistance of the wires[22] are extremely low, about 1% or less. As a result, wiring is not considered further.

[22] The electrical resistance is a function of the electrical resistivity and wire cross sectional area and length of wiring

The light fixtures, assumed to be LED, lose around 30-60% of the energy converting the electricity into light shining in the required direction. The luminous efficacy, measured in lumens per Watt (lm/W) is used to measure this. There are also secondary light performance characteristics that are required to ensure the lighting is suitable for the application and can influence luminous efficacy. These include the colour rendering index (CRI)/chromaticity, colour temperature and light distribution.

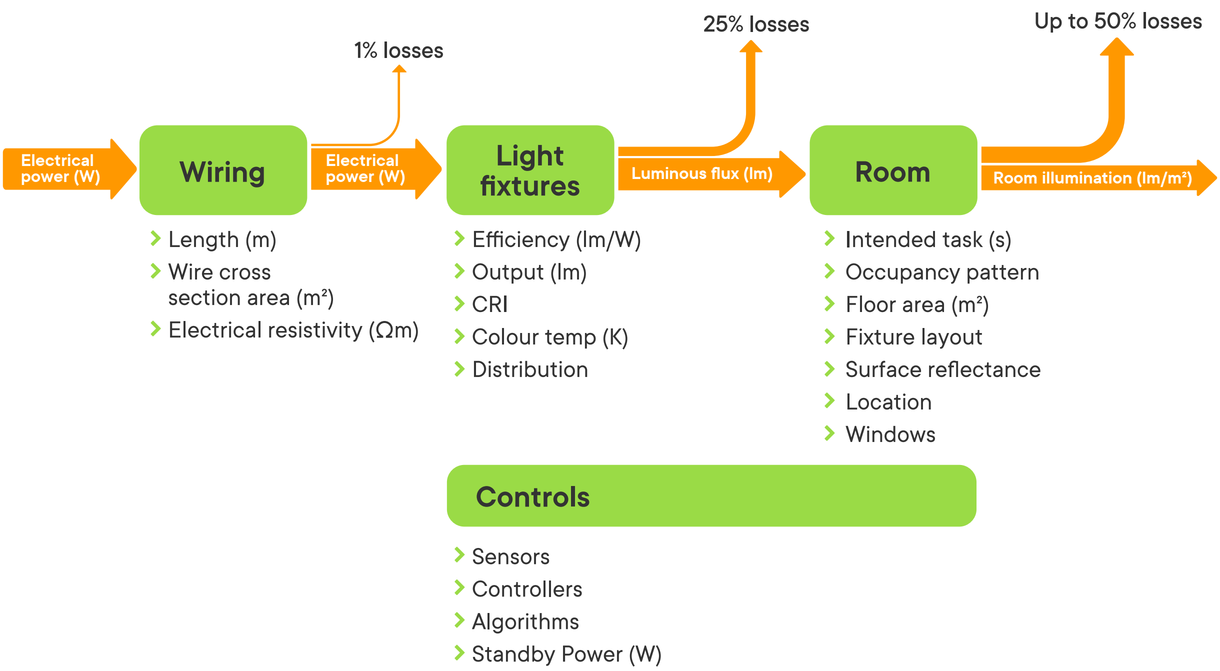
Additional losses of up to 50% occur as a result of excess illumination in the room, measured in lumens per floor area (lm/m²). This occurs when the lighting is too bright for the application or when the space is unoccupied. The amount of illumination light required depends on the intended application(s) of the space as well as individual preferences and the occupancy pattern. To assess this loss, it is necessary to specify the lighting requirements.

The illumination provided to the room can be split into:

- external sources, mostly daylight but also light from adjoining rooms if walls are transparent. This is determined by the geographic location (latitude and climate), window[23] size, orientation and glass transmittance, and any shading from nearby buildings, trees or blinds.
- artificial illumination installed in the room. This is determined by the light fixture luminous output, the number and layout of fixtures in the room.

The surface reflectance of the walls, floor and work surfaces will also influence the illumination needed.

Figure 1: Lighting system parts and Sankey diagram



Lighting control strategies can reduce the amount of excess illumination, and require sensors, dimmers, and control logic to manage the lights. There is additional energy consumed for the control equipment in both active and network standby modes. The energy consumed by the controls are all converted to heat and can be considered losses.

[23] Including skylights and rooflights

4.2 Specifying lighting system performance requirements

The required lighting performance levels need to be set in order to assess whether a system is efficient. ISO 8995-1:2002 specifies lighting requirements for indoor workplaces and for people to perform the visual tasks efficiently, in comfort and safety throughout the whole work period. An update is under development;

ISO/CIE DIS 8995-1 Light and lighting of workplaces Part 1: Indoor. This is described as specifying[24] "requirements for lighting solutions for most indoor workplaces and their associated areas in terms of quantity and quality of illumination. The illumination can be provided by daylight, electric light or a combination of both. Recommendations are given for good lighting to fulfil the needs of integrative lighting. This standard neither provides specific solutions nor recommendations for atmosphere or aesthetics created by lighting. It does not restrict the designers' freedom from exploring new techniques nor restrict the use of innovative equipment." As of February 2024, the status of the standard is described as 40:60 (enquiry stage, close of voting).

4.3 Testable parts and standards

4.3.1 Light fixtures

The major testable part is the lights. The performance of lights is tested under standards LM79[25] (2008) and EN 13032-4[26] (2015) for total luminous flux, luminous efficacy, luminous distribution, colour temperature, and CRI/chromaticity.

Efficiency (luminous efficacy) is generally measured at max output, but the test standard does not preclude testing dimmable bulbs at different luminous output levels. The NLC specification (described below) requires that all lights are dimmable, and that the luminous efficacy curve be provided by manufacturers.

Because LEDs dim and lose efficiency over time the lumen maintenance is also measured. Some lights compensate for this by increasing power as it ages to maintain light output. The Illuminating Engineering Society of North America (IESNA) approved standard for measuring lumen maintenance of LED light sources, LM80, can be used to measure this.

4.3.2 Sensors and controls

Digital controls will have network standby, but the applicable test standard is not clear. Under EN 50564:2011 Electrical and electronic household and office equipment – Measurement of low power consumption, lighting is not considered to be household or office equipment. However, there is a clause in the scope for "other equipment" which allows it to be used for lighting. It is possible that IEC 63103:2020[27], applies; this, which specifies methods of measurement of electrical power consumption in non-active mode(s), is applicable for electrical lighting equipment (this includes electrical lighting equipment incorporating non-illumination components).

There is some research on testing occupancy sensors (Feagin et al, 2020). The National Electrical Manufacturers Association (NEMA) developed the only known standard, to test occupancy and motion sensor performance NEMA WD 7-2011 (NEMA 2016). However, the US Department of Energy reported some concerns with the NEMA protocol (e.g. strict height and weight limits on test subjects, large amounts of manual effort, sometimes inconsistent repeatability) (US DoE 2022).

No testing standard for the overall control system has been identified.

[24] https://www.iso.org/standard/76342.html
[25] LM79 is the Illuminating Engineering Society North America (IESNA) approved testing method to generate electrical and optical measurements of solid state lighting (LED) products. is applicable to integrated LED products, such as luminaires and replacement lamps.
[26] 2015 Light and lighting - measurement and presentation of photometric data of lamps and luminaires. LED lamps, modules and luminaires
[27] The US equivalent is ANSI C137.63103-2021

D4i certified LED drivers[28] provide diagnostic data (fault codes, temperature etc) to the communication node: Part 253 Ability to monitor the health of luminaires on a continuous basis to anticipate maintenance needs.

4.3.3 Lighting systems

The National Electrical Manufacturers Association (NEMA) sponsored ANSI Lighting Systems Committee (C137)[29] have developed several standards for lighting systems. The published standards relevant to indoor lighting systems[30] are:

- C137.0 – Lighting Systems - Lighting Systems Terms and Definitions (2022)
- C137.1 – Lighting Systems - 0-10V Dimming Interface for LED Drivers, Fluorescent Ballasts, and Controls (2022)
- C137.3 – Minimum Requirements for installation of Energy Efficient Power over Ethernet (PoE) Lighting Systems (2017)
- C137.4 – Lighting System Digital Interface with Auxiliary Power (2021)[31]
- C137.5 – Lighting Systems - Energy Reporting Requirements for Lighting Devices (2021)
- C137.6 – Lighting Systems - Data Tagging Vocabulary (Semantic Model Elements) For Interoperability (2021).

ANSI C137.5 specifies the minimum performance requirements for lighting devices that report energy data. These requirements include the specific energy data types to be reported, the nominal and statistical accuracy performance for all reported data types, and references to other standards that define the information model for all data types.

Other ANSI standards reported as being under development[32] are:

- C137.8 – Lighting System User Interfaces
- C137.9 - Networked Lighting Systems Configuration Report
- C137.10—Sensor Data Models for Lighting Systems.

There do not appear to be any international (EN) equivalents to these ANSI standards.

4.4 Untestable parts and modelling (excluding daylighting and windows)

The major untestable parts are the room and controls. There are two parts to the modelling: the performance and the energy efficiency. Performance modelling determines if the lighting system design meets the minimum target illumination levels (and other performance factors) determined by the room application. Standard occupancy times are also defined. The energy efficiency modelling calculates how much energy (or power is consumed).

CIE 52[33] (1982) and EN12464-1[34] (2021) give guidance on how to calculate the illumination provided for different applications and check it meets the lighting performance requirements. The illumination level across the room is calculated by dividing the floor into a grid and the illumination level for each point on the grid is determined based on the layout of lights and how each one contributes to the illumination at each point. These can be time consuming to calculate manually but can easily be implemented in spreadsheets or software.

Current lighting model capability is described in Section 3.4.

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[28] D4i certification is provided by DALI Alliance members who operate Networked Lighting Controls - described in section 3.6 below. https://www.dali-alliance.org/d4i/#D4iSpecs

[29] https://www.nema.org/standards/technical/ansi-c137-lighting-systems-committee

[30] Others are for specifically for lighting for parking

[31] Compatible with DALI – see below

[32] https://www.energy.gov/eere/ssl/voluntary-standards-and-specifications-support

[33] International Commission on Illumination (CIE) Calculations for Interior Lighting Applied Method

[34] Light and lighting. Lighting of work places Indoor work places

4.4.1 Room

Because the room will vary with every system, standardised testing of every room is not possible. Some characteristics such as the glass transmittance can be tested but modifications such as window films, shading and even cleaning frequency can affect the result. Some lighting models can incorporate the effects of shading – both intrinsic, due to the layout of the buildings and surrounding structures and the effect of blinds introduced to reduce glare.

4.5 Integrating testable parts into modelling

As discussed above the most commonly used standards for lighting systems in building regulations, IECC and EN 15193-1 (2017), calculate the energy consumption by lighting systems. It must be assumed or separately established that the lighting performance requirements have been met since this is not covered in these standards. The calculations in the standard use the room floor area, number of lights and power demand of each light.

The power/energy used is calculated solely from the power of the lighting, measured for each lamp. Models such as DIALux contains an extensive database of lights and their performance characteristics. There is a standard for the data format for each lamp, EN 13032[35]; if followed this ensures that the data for each lamp is consistent.

EN 15193-1 (2017) can also take into account the levels of daylight using a simple or more comprehensive approach to calculate annual energy consumed per year. The latter is still thought to underestimate the contribution daylight can make and therefore overestimate the artificial light needed (Lo Verso et al, 2018).

EN 15193-1 is described more fully in the Annex.

4.6 Artificial lighting requirements and modelling including daylight

Daylighting can reduce the amount of artificial lighting. The following room characteristics influence the quality, quantity and utility of daylight in a space:

- Room size and shape
- Window/roof light size, location, aspect and transmissivity (which can depend on window cleanliness)
- Window shading (to reduce glare, solar heating)
- Latitude
- Climate
- Use profile of the room relative to daylight hours.

ISO/CIE DIS 10916 (2023)[36] defines the calculation methodology for determining the monthly and annual amount of usable daylight penetrating non-residential buildings through vertical facades and rooflights and the impact thereof on the energy demand for electric lighting. For estimating the daylight supply and rating daylight-dependent artificial lighting control systems, a simple table-based calculation approach is provided. It includes a simple method which describes the division of a building into zones as required for daylight illumination-engineering purposes, as well as considerations on the way in which daylight supplied by vertical facade systems and roof lights is utilised and how daylight-dependent lighting control systems affect energy demand. Dynamic vertical facades with optional shading and light redirection properties are considered, i.e. allowing a separate optimization of facade solutions under direct insolation and under diffuse skies. For roof lighting systems standard, static solutions like shed roof lights and continuous roof lights are considered. It does not take into account additional controls, for example occupancy controls.

[35] Light and lighting. Measurement and presentation of photometric data of lamps and luminaires. In four parts of which part 4 is Light and lighting. Measurement and presentation of photometric data of lamps and luminaires. LED lamps, modules and luminaires, 2019

[36] Light and lighting – Energy performance of lighting in buildings — Calculation of the impact of daylight utilization

EN 17037[37] (2018) sets standards for individual spaces within a building and recognises that optimal daylighting varies by room type. Performance levels are established for each of four daylighting design criteria: daylighting, views, access, and glare. These criteria establish a minimum acceptable daylighting environment for building occupants and address health, comfort, and productivity. The daylighting provision requires that adequate natural lighting, defined as 300 lux of natural light, should be present for building occupants to be able to perform regular tasks. A space is deemed compliant if it is calculated to achieve a minimum of 300 lux over 50% of the space for more than half the daylight hours in the year without artificial lighting (US National Institute of Health 2019).

4.7 Current lighting policies and modelling applications

The current standards and models are already used in policies. These policies could be combined with other MEPS or functionality criteria for parts and subsystems. In addition, all these requirements could be integrated into an overall legal framework to establish responsibilities, procedures and compliance mechanisms. Two standards and approaches for lighting systems are described in the Annex.

The most notable features of other policies relevant to this project are summarised below, with more detailed descriptions in the Annex.

4.7.1 Networked Lighting Controls voluntary specifications

Networked Lighting Controls[38] (NLC) is a voluntary programme which sets minimum functionality specification for lighting systems, in a similar way to the EU smart readiness indicator. This includes the types of sensors, lighting controllability, user interface and control strategies. At the highest level, luminaire level lighting control (LLLC) is recommended which enables each light to be controlled with its own sensors.

In addition, they have recommended but not yet defined standardising monitoring and reporting of system performance data. The aim of this is to enable better comparison and analysis of data and energy savings between buildings.

NLC also has the potential to auto-configure the most common controls and simplify calibration, e.g. using a tablet to interface with the system while configuring and calibrating the system.

NLC suggests a possible route to use sensor and control technologies to:

- simplify and improve installation quality (auto-configuration) and also reduce verification checking.
- standardise reporting to improve monitoring and reporting to assess energy savings.
- establish interoperability standards between devices.

A more detailed description of the voluntary specification is in the Annex.

4.7.2 US BRIGHT Act – mandated government procurement guidelines

This US act[39], passed 17 October 2022, "Bulb Replacement Improving Government with High-efficiency Technology Act" or the BRIGHT Act, expands requirements relating to the procurement and use of energy-efficient lighting in federal buildings.

Under previous law, public buildings that are constructed or managed by the General Services Administration (GSA) must be equipped with energy-efficient light bulbs and fixtures. Under the new act, buildings must be equipped with the most life-cycle cost effective and energy-efficient lighting systems available, including with respect to sensors, fixture distribution, and other elements. The Act also specifically establishes requirements relating to the procurement of such lighting systems and modifies other requirements accordingly:

[37] Daylight in Buildings
[38] Operated by DLC, https://www.designlights.org/, an independent nonprofit organisation
[39] https://www.congress.gov/bill/117th-congress/senate-bill/442

- Uses a life cycle cost approach rather than setting a MEPS or minimum functionality.
- Provides guidance and examples for making financial and technology-based decisions, noting the diminishing returns for additional controls.
- Recognises the need for regular updates and retro commissioning as there are many changes that affect the efficiency of the system including:
  - New control system firmware and features
  - Building changes
  - Changes to use
  - Renovations affecting surface finishes and reflectance.
- Requires periodic retro commissioning to determine changes every two to five years.

4.7.3 Existing building code: ASHRAE 90.1 2022

The International Energy Conservation Code (IECC) is referred to as a model energy code because building codes are state or local laws; there is no national building energy code in the USA. It is updated every three years.

For commercial buildings, American National Standards Institute (ANSI) standard ASHRAE 90.1 is considered the model code. It is published every three years with updated requirements; 2022 is the most recent edition.

This building code approach:

- Establishes a precedent for regulating alterations to existing lighting systems and requires installation of controls when significant changes to other parts (e.g. lamp replacement) occurs.
- Uses a basic model that excludes usage patterns and daylighting; the latter could vary greatly in USA depending on latitude and climate.
- Sets prescriptive control requirements that may not be optimally efficient or most cost effective but should ensure a minimum performance is achieved.
- Sets verification and testing requirements to ensure controls operate as intended.

A fuller description of the lighting system requirements in ASHRAE 90.1 is in the Annex.

4.7.4 EU Energy Performance of Buildings Directive (EU) 2018/844 technical guidelines for establishing and enforcing technical building system requirements

Technical building systems (TBSs) are defined in the Energy Performance of Buildings Directive (EPBD) as 'technical equipment for space heating, space cooling, ventilation, domestic hot water, built-in lighting, building automation and control, on-site electricity generation, or a combination thereof, including those systems using energy from renewable sources of a building or building unit' (Article 2(3) of the EPBD).

The performance of technical building systems has a significant impact on overall building energy performance, therefore, one of the aims of the EPBD is to ensure that technical building system performance is optimised. In particular:

- Article 8(1) requires Member States to set system requirements on overall energy performance, proper installation, appropriate dimensioning, adjustment and control of technical building systems.
- Article 8(9) requires Member States to ensure that when a technical building system is installed, replaced or upgraded, the overall energy performance of the altered part or (where relevant) of the complete altered system is assessed.

The European Commission commissioned research to establish technical guidelines to help Member States put these provisions into practice; these were published as Van Tichelen et al (2023). Compared to the US building code the guidelines are more flexible and seem to try to achieve a higher level of system optimisation. Another key difference is that verification of controls is substituted by monitoring.

Key points of the guidelines are:

- They require detailed modelling for lighting performance requirements and efficiency expressed as LENI where possible (rather than LPD) based on exact building requirements, usage etc .
- Multiple options for minimum controls requirements.
- Detailed design and performance documents should be submitted. These should include LENI calculated for at least per every 200 m² and parasitic power.
- Adjustment and installation quality requirements include measurement of factors affecting efficiency such as surface reflectance and illuminance values. However, the checking of controls is based only on a declaration of honour.
- Metering and monitoring of both quarterly LENI and instantaneous LPD are required to check variation in power is occurring seasonally and between summer and winter indicating daylight controls are effective.
- Monitoring of occupancy with at least one alternative parameter, e.g. lift operation, ICT up-time, etc.

The technical guidelines are described in more detail in the Annex.

4.8 Lighting requirements for non-residential buildings in the California building Code

California building codes were examined for two reasons:

1. They are recognised as being amongst the most stringent in the United States, reflecting the State's strong ambitions to reduce carbon emissions[40].
2. A previous project (Wu et al 2022) identified the commissioning tests for lighting systems in the Californian building code as a possible way of checking system performance.
3. Unlike the EU guidelines and US model codes they are in effect and have been proven to be implementable in real life, with associated supporting tools, training and inspections.

The most recent edition of the code is 2022 (California Energy Commission 2022a) and it is this version of the Code that is described below. New requirements for lighting systems in this version (California Energy Commission 2022b) include:

- mandatory occupant sensing control requirements for office spaces greater than 250 ft² (23.2 m²)
- automatic daylighting controls for secondary sidelit daylit zones now mandatory

4.8.1 Building code requirements for lighting and lighting controls

Users can take one of two options to comply with the California Code requirements on lighting efficiency:

1. A prescriptive approach – a maximum power is set based on the area and use of the space. The power can be adjusted by special allowances such as for display lighting and decorative or ornamental lighting and the use of controls which exceed the requirements of the energy code.
2. A performance approach which is more flexible, using approved software and allows trade-offs between different energy systems (note it does not allow trade-offs between lighting systems in different parts of the building).

[40] For example, in 2006 they adopted legislation requiring California to reduce its overall greenhouse gas emissions to 1990 levels by 2020 and 40% below 1990 levels by 2030 and appointing the California Air Resources Board to develop policies to achieve this goal.

Most lighting alteration projects have to meet these requirements (as well as new projects).

The controls required are described in the code as follows:

4.8.1.1 Manual Area Controls

The luminaires in each area must be independently controlled by manual lighting controls that provide on/off functionality.

4.8.1.2 Multilevel Lighting Controls (dimmers)

Dimmable lighting provides the opportunity to reduce lighting energy use while allowing occupants to choose an appropriate light level for each area at any time. Dimmers are required in most spaces with exceptions including: any area less than 100 ft² (9.3 m²), connected lighting load of 0.5 W/ft² or less. The number of mandatory control steps is based on the light source type; for example, LED luminaires are required to offer continuous dimming between 10–100%; High Intensity Discharge luminaires to have as a minimum one step between 50–70%.

4.8.1.3 Shut-off Controls

Shut-off controls automatically reduce lighting power when a space is unoccupied. These controls are required in addition to the manual area lighting control and multilevel control requirements (described above). For buildings not in continuous operation, almost all lighting should be off when a building is unoccupied for 20 minutes or more. Lighting must be controlled by one or more of the following types of automatic shut-off controls:

- Automatic time switches
- Occupant sensing controls
- Other control capable of automatically shutting off all of the lighting when the space is typically unoccupied, such as an Energy Management Control System.

Lighting in each enclosed area and every building floor (except in stairwells) must separately and automatically shut off when the building is vacant. In addition, no more than 5 000 ft² (464.5 m²) may be covered by a single control.

4.8.1.4 Daylighting Controls

Space that are lit by daylight (from a skylight, directly by windows or areas not directly adjacent to a window but close enough to still receive some daylight) general lighting must be adjusted with automatic daylighting controls that:

- Provide multilevel lighting (as described above).
- Maintain design light levels for each space (i.e., at or above those provided by electric lighting when no daylight is available).
- Reduce general lighting power in a daylit zone by at least 90% when the daylight contribution in that zone is more than 150% of the general lighting system's design light level at full power.

When photosensors are located within the daylit zone, at least one photosensor must be located so that they are not readily accessible to unauthorised personnel.

4.8.1.5 Demand Responsive Controls

Demand response controls are used to reduce peak demand and stabilise the electricity network. Buildings that have 4 000 W of installed lighting load or greater must include demand responsive controls in spaces that are equipped with multilevel lighting controls. Participation in utility demand response programmes is not required. The Energy Code requires that the controls be capable of communicating with a Virtual End Node using a wired or wireless bi-directional communication pathway. For compliance testing, the lighting controls must be able to demonstrate a 15% or greater reduction in lighting power.

4.8.1.6 Control Interactions

The Code specifies how the controls should interact, as follows:

1. For general lighting, the manual area control must permit the amount of light provided while the lighting is on to be set, or adjusted, by the multilevel, shut-off, automatic daylighting and demand responsive controls.
2. The manual area control must permit the shut-off control to turn the lighting down or off.
3. The multilevel lighting control must permit the automatic daylighting control to adjust the electric lighting level in response to changes in the amount of daylight in the daylit zone.
4. The multilevel lighting control must permit the demand responsive control to adjust the lighting during a demand response event and to return it to the level set by the multilevel control after the event.
5. The shut-off control must permit the manual area control to turn the lighting on. If the on request occurs while an automatic time-switch control would turn the lighting off, the on request must be treated as an override request.
6. The automatic daylighting control must permit the multilevel lighting control to adjust the level of lighting.
7. For lighting controlled by multilevel lighting controls and by occupancy sensing controls with an automatic-on function, the controls shall provide a partial-on function that is capable of automatically activating between 50–70% of controlled lighting power.

4.8.1.7 Metering and separation of electrical load

The code requires lighting electrical load to be separated depending on the size of the electricity demand as follows:

- rated 50 kVA or less, not required
- rated more than 50 kVA and less than or equal to 250 kVA, all lighting in aggregate
- rated more than 250 kVA, all lighting disaggregated by floor, type or area.

Separation of electrical loads, when required, allows for measurement devices to monitor electricity usage for different load types; however, the code does not require separate metering. Overall metering requirements are Instantaneous (at the time) kW demand and tracking kWh for a user-definable period.

4.8.2 Products regulated under the Energy Code:

The following lighting control devices are regulated under the Energy Code only (not under appliance efficiency regulations[41]):

- Lighting control devices
- Time-switch lighting controls: automatic time-switch controls, astronomical time-switch controls, multilevel astronomical time-switch controls, outdoor astronomical time-switch controls
- Daylighting controls: automatic daylight controls, photo controls
- Dimmers
- Occupant sensing controls: occupancy sensors, motion sensors, vacancy sensors, partial-on sensors, partial-off sensors
- Indicator lights
- Track lighting integral current limiter
- Supplementary overcurrent protection panels for use with line-voltage track lighting.

[41] From California Lighting Technology Center 2023

These requirements are functional with no reference to test standards. For example, Daylighting controls; controls that provide automatic daylighting functionality shall:

A. Automatically return to its most recent time delay settings within 60 minutes of the last received input when left in calibration mode;
B. Have a set point control that easily distinguishes settings to within 10 percent of full-scale adjustment;
C. Provide a linear response within 5 percent accuracy over the range of illuminance measured by the light sensor; and
D. Be capable of being calibrated in a manner that the person initiating the calibration is remote from the sensor during calibration to avoid influencing calibration accuracy, for example by having a light sensor that is physically separated from where the calibration adjustments are made.

4.8.3 Certification process for lighting in California building regulations

Note that while the regulations are set at State level the permitting authority (responsible for enforcing regulations) is the relevant City or County government.

The major steps in certifying that the lighting in a non-residential building meets the building energy efficiency requirements (EnergyCodeAce 2022) for full commissioning are:

1. On completion of building design, the design (including lighting) has to be certified as complying with the building code.

   The certifier can be the Engineer or Architect of Record for buildings < 10 000 ft² (approximately 929 m²), a Qualified In-House Engineer or Architect (with no other project involvement) for buildings 10 000 – 50 000 ft² (4 645 m²). For buildings > 50 000 ft² the certifier needs to be a Third-Party Engineer, Architect, or Contractor.

2. At the permitting stage commissioning measures need to be identified for all aspects affecting the energy use of the building as part of the construction documents. For larger, ≥ 10 000 ft² buildings, a commissioning plan is required which includes:

   - Equipment and systems to be tested, including the extent of tests
   - Functions to be tested
   - Conditions under which the tests must be performed
   - Measurable criteria for acceptable performance.

   This forms part of the permit application.

3. Post construction for buildings: for floor area < 10 000 ft² acceptance and verification testing is required. For ≥ 10 000 ft² buildings a Commissioning Report is required which must include:

   - Functional Performance Testing and Documentation. For some systems, termed 'covered processes', this includes Acceptance Testing. Lighting controls are a covered process.
   - An Operations and Maintenance (O&M) Systems Manual
   - Systems Operation Training
   - A Commissioning Report.

4. The permitting authority's building department field inspector verifies that the building construction follows the plans and specifications that were approved when the building permit was issued. Once final inspection is complete, the Certificate of Occupancy is issued.

Commissioning is not required for additions to existing buildings or alterations of existing buildings.

4.8.4 Acceptance testing for lighting controls

The building code appendices (California Energy Commission, 2022c) include NA7 Installation and Acceptance Requirements for Nonresidential Buildings and Covered Processes, which includes acceptance testing for lighting controls. Certified Lighting Controls Acceptance Test Technicians (CLCATT) are required to review and test newly installed lighting systems to ensure the controls and connected loads operate as required by the Energy Code. CLCATT are required to be trained and certified through a state-approved programme. The California Energy Commission's approved Acceptance Test Technician Certification Providers (ATTCP) train, certify, and oversee the technicians and their employers. The National Lighting Contractors Association of America is the ATTCP for lighting controls.

Acceptance Testing takes place after controls have been installed and commissioned. Functional test results must be included in commissioning documents when required.

Acceptance testing is required for the following lighting control systems:

- Automatic daylighting controls
- Occupancy sensors
- Demand responsive controls
- Institutional tuning controls used to earn a power adjustment factor (PAF[42]).

The testing requirements are described in the CEC Annex; for example, continuous dimming controls are to be tested in full, partial and no daylight. The degree of testing depends on the size of the installation. For example, for daylight controls:

- All photocontrols serving more than 5,000 ft^2 (465 m^2) of daylit area shall undergo functional testing.
- Photocontrols that are serving smaller spaces may be sampled as follows:
  - For buildings with up to five (5) photocontrols, all photocontrols shall be tested.
  - For buildings with more than five (5) photocontrols, sampling may be done on spaces with similar sensors and cardinal orientations of glazing; sampling shall include a minimum of one (1) photocontrol for each group of up to five (5) additional photocontrols. If the first photocontrol in the sample group passes the functional test, the remaining photocontrols in the sample group also pass. If the first photocontrol in the sample group fails the functional test, the rest of the photocontrols in the group shall be tested. If any tested photocontrol fails the functional test, it shall be repaired, replaced or adjusted until it passes the test.

Acceptance testing is required for new buildings and for alterations where controls are added to > 20 luminaires for the entire permitted project.

4.8.5 California building code supporting documents and tools

An extensive library of supporting material is provided including:

- 2022 Energy Code Compliance Manuals and Forms (California Energy Commission 2022d) which contain information supplemental to the 2022 Energy Code regulations. The manuals are intended to help plan examiners, inspectors, owners, designers, builders, and energy consultants comply with and enforce California's 2022 Building Energy Efficiency Standards.
- The California Energy Commission Online Resource centre[43] which provides:
  - Compliance forms
  - Videos

[42] Described in the section on lighting regulations.
[43] https://www.energy.ca.gov/programs-and-topics/programs/building-energy-efficiency-standards/online-resource-center

- Other resources and training materials
- A listing of approved energy analysis compliance software to use for demonstrating compliance with the performance method[44].
- A listing of equipment certified by manufacturers that meet the requirements of the energy code. These include demand responsive lighting controls as these are required to be certified by the manufacturer as being capable of responding to signals from an OpenADR[45] 2.0b Virtual End Node
- Listing of a free phone hotline and email address for support.

- Nonresidential lighting and electrical power distribution, A guide to meeting or exceeding California's 2022 Building Energy Efficiency Standards (California Lighting Technology Center 2023).
- The California Energy Commission Acceptance Test Technician Certification Provider Program – ATTCP webpage[46]. This programme is described above. The webpage provides program information, reports and links to certified training providers.
- The Modernized Appliance Efficiency Database System, MAEDbS[47], which was created for California's Appliance Efficiency Program. Regulated appliances can only be installed if they are compliant and listed on this database. (Most types of lamps, ballasts and luminaires are regulated; lighting controls are not.)
- California Building Energy Code Compliance (for Nonresidential and Multifamily buildings) software, CBECC[48]. This is an open-source software program developed by the California Energy Commission for use in complying with the Title-24 Non-Residential Building Energy Efficiency Standards. The software can generate the standard design model for a given user model and perform the annual energy analysis comparing its energy efficiency relative to the 2022 Standards.
- The EnergyCodeAce website[49] which:
  - provides downloadable fact sheets, checklists and forms
  - includes Forms Ace which helps users identify which Energy Code forms are relevant for their project
  - gives access to the Virtual Compliance Assistant which can be used to complete forms and verify compliance prior to submitting forms to the Authority Having Jurisdiction for non-residential projects
  - gives access to free live and recorded online training.

All these resources are provided free of charge.

4.8.6 Commentary on the lighting regulations in the California non-residential building energy code

The California energy code is a step towards a full energy system approach for non-residential lighting. It does not specify energy use in energy/area illuminated per year but by specifying mandatory controls more tightly than other regulations it should access greater energy savings, without additional modelling or monitoring requirements.

The effectiveness of regulations is likely increased by the stringency of documentation required at each stage of the process, design, building and commissioning. In principle these steps ensure that the lighting controls match those in the design (which has been certified as meeting code requirements) and they have been installed and commissioned correctly. Thus, the requirements for documentation and testing substitute for requirements to model and/or monitor, at least in part.

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44 There are currently three approved models: CBEEC (described below), EnergyPro 9.2 and IES 1.1
45 OpenADR is an open, highly secure, and two-way information exchange model and global Smart Grid standard.
46 https://www.energy.ca.gov/programs-and-topics/programs/acceptance-test-technician-certification-provider-program
47 https://cacertappliances.energy.ca.gov/
48 https://bees.noresco.com/
49 https://energycodeace.com/ Funded by California utility customers and administered by Pacific Gas and Electric Company (PG&E), San Diego Gas & Electric Company (SDG&E®), and Southern California Edison Company (SCE) under the auspices of the California Public Utilities Commission.

It is noteworthy that there is an extensive support for practitioners to help them meet the Californian building energy code requirements. The difference sources are listed above to make that clear. The quantity and quality of material is unusual in the authors' experience. This suggests that adopting this approach requires regulators to provide more resources to enable industry to comply.

4.9 Research on using lighting control system metering for building code compliance

The project "Verifiable Performance for Networked Lighting Systems" was part of some work undertaken by Lawrence Berkley National Laboratory for the State of California (Brown et al 2020). Their main findings are reported below.

4.9.1 Researcher proposal for performance metric for lighting systems

"In building energy code requirements for commercial lighting systems, an outcome-based code model would move from lighting power density (LPD) prescriptions to energy usage intensity (EUI) prescriptions for different use cases and space types.

LPD (watts/ft^2) as the focus of building energy code requirement is an incomplete and imperfect option. Consider that a high-wattage lighting system that is rarely on or is always operated at dimmed or reduced power, (analogous to partial load performance of a chiller) may be less energy intensive than a lighting system with a lower "nameplate" wattage that is operated continuously at full load. Especially with the state of dimmable modern lighting technologies, the simplified concept of lighting power density as a catch-all lighting performance metric loses meaning.

A more effective metric for capturing the actual energy effect of a lighting system over time is EUI (kWh/ft^2/year). Like LPD, it is normalised to the building area, but unlike LPD, the energy usage intensity of a system is not bound by the nameplate performance at maximum load, but rather reflects the actual operating characteristics of a system over time. Annual EUI reflects the total energy usage over that timeframe without respect to simple installed power density totals."

Note that EUI is used as a metric in the US to benchmark building energy performance[50]. It is calculated in the US EPA ENERGY STAR Portfolio Manager. Thus, is it a familiar concept for US building and lighting practitioners. The same metric (named lighting energy numeric indicator and expressed as kWh/m^2/yr) is used in EN 15193-1 2017 (described above).

4.9.2 Outcome-Based Code Compliance Through Software Validation and Self-Reporting

Using EUI as a metric requires measuring the energy usage of a system, post-installation and through time in a way without excessive measurement and verification effort. With the advent of energy reporting features from many networked lighting control systems, it is possible in theory to track lighting energy outcomes directly by a new lighting system ex post. If self-reported demand and energy usage from lighting systems are found to be reliably accurate (within an acceptable tolerance), building codes for lighting systems could use this to verify performance against EUI.

LBNL undertook an experiment, operating three advanced networked lighting controls systems with energy reporting capabilities (measured or calculated), and comparing reported lighting energy use from the controls system to test lab -measured lighting energy. In one case the controller provides energy data based on a calculated method; in other words, the system does not directly measure energy throughput from controller to light fixture, but calculates it based on assumptions regarding lighting load at different control conditions. This system relied on user inputs during commissioning to calculate the energy usage values that were reported by the system software. The nameplate full power wattage of the LED fixtures

[50] https://www.energystar.gov/buildings/benchmark/understand_metrics/what_eui

controlled by the system was entered into the commissioning software. The other two systems used system data directly.

The two systems which used system data directly showed reasonable accuracy: one had a daily error of 0.5%, the other 7.9%. The system which used a model was much less accurate with a daily error of 27.7%. The authors concluded that "Based on this work, it does appear that networked lighting controls, if designed and installed properly, can be used for determining energy performance of lighting systems for outcome-based code. Reliability is not guaranteed, however, as the variations in daily errors among the systems show. The accuracy of a system's energy reporting feature should be verified prior to its use as a means of validating energy performance over time."

Note that this leaves the outstanding issue of how to verify the accuracy of a system's energy reporting without the lab testing that LBNL undertook.

4.10 Proposed approaches for regulating lighting systems

4.10.1 Summary of the current situation and rationale for suggested approaches

The lighting requirements in most building regulations in 4E countries to date are relatively simple: they specify a level of lighting for particular applications and the maximum energy that can be used to achieve them and so do not require the use of models. They require controls in certain situations – based on occupation or responding to daylight levels but not prescriptively and there is generally no detailed commissioning and checking of installed controls. This means that most of the energy savings from controls: daylight sensing, occupation (sensors or timers) and tuning (dimming) are not accessed by regulations. Further, building applications change and designers, owners and operators of a building tend to over budget on lighting (within the building regulation requirements) so that if applications change or if/when the performance of the lighting degrades over time, they will be able to provide adequate light without installing new lamps. Without prescriptive mandatory controls this increases energy losses further.

There are lighting models which are widely used, for lighting design and in demonstrating that systems meet the requirements of building regulations in 4E countries. However, the more sophisticated aspects of lighting models have not been required to meet regulations. There is a standard to validate models, but this is known to be flawed.

Mandatory monitoring of lighting systems has not been used in building regulations or, from this research, in voluntary approaches such as procurement guidelines, in 4E countries. Building regulations generally require separate metering for lighting but do not go beyond this to require sub-metering of circuits in different areas of buildings in a way that would enable monitoring of lighting systems.

In a limited search we have found few papers or reports on the monitoring of lighting systems. Monitoring is used to verify energy savings for utility energy efficiency (described above). This is done at a single point, following installation and commissioning, relatively simple and limited. Also LBNL have monitored lighting systems as part of their work for the California Energy Commission (Brown et al 2020) described above, but this was under laboratory conditions.

Based on this research modelling and monitoring, separately or together, are not currently robust enough to be used in for regulating the energy efficiency of lighting systems. We therefore suggest a two-pronged approach – in the short term adopt enhanced building regulations, requiring additional controls and acceptance testing, in line with the most recent California Energy Code. At the same time address the points which prevent monitoring and modelling being adopted in regulations so that they can be used in future. These two approaches are described below.

4.10.2 Immediate approach – enhanced building regulations with mandatory controls and acceptance testing

In this approach enhanced building regulations are adopted. Three regulations have been reviewed in this research: ASHRAE 90.1, Technical guidelines for EU EPBD, and California Energy Commission. The last of these appears to be the most comprehensive so these are taken as the exemplar to follow. This means more efficient lighting systems are achieved by:

- Regulating alterations to existing system and new systems.
- Requiring controls (daylight, shut off (occupancy, timing) and demand response) in circumstances where they are likely to save energy (with some concessions for small spaces)
- Setting functional requirements for these controls (in the absence of test standards. If test standards are developed these could be adopted).
- Rigorous checks that building designs meet regulatory requirements.
- Third party acceptance testing which checks that lighting is installed as designed and lighting controls operate as required.

This is a pragmatic approach which does not need modelling or test standards for controls – testing is functional. It is possible for modelling to be used if the performance approach is adopted but third-party acceptance is still needed.

As the burden of proof that lighting systems are energy efficient is largely documentary significant support to the industry: architects, designers, contractors, certifiers; is required to help them achieve this. This will need to include guidelines and training as well as training and certification for acceptance testers.

One downside to this approach is that the energy savings from the controls are not quantified. In some jurisdictions it may be difficult for regulations to require the cost of controls (less in terms of capital costs as these are relatively low, more the cost of designing installing, commissioning and testing) without this.

4.10.3 Longer term solution –using a combination of modelling and monitoring and acceptance testing

There are already lighting system models which are used on a voluntary basis to help meet building regulations in 4E countries. Monitoring is used to check energy performance for utility energy savings schemes in 4E countries (see Section 3.9) and research (Brown et al 2020) has shown that lighting systems can provide accurate energy use data, removing the need for additional monitoring with associated energy and economic costs. This suggests that there is potential for regulating lighting systems using a combination of:

- (certified) models to check that the design meets regulatory requirements,
- acceptance tests (as used in the California Energy Code) to check the installation is in line with the design, and
- monitoring, using system energy reporting, to check that the system is behaving as designed initially. Ideally the monitoring will continue, perhaps reported annually to the enforcement authority to check that performance hasn't deteriorated so that the system no longer meets requirements.

Over time there may be valid reasons for the energy use to change; the lighting use may be different from that expected or change and the environmental conditions may change[51]. The lighting energy use may go up (or down) due to this but the lighting system could still be compliant with regulations. The combination of modelling and monitoring could be used to check this. The differences (hours of occupation, daylight levels) would be documented by the lighting system automatically, and/or by the building operator/occupier. These data could be used to update the model to check that the system still meets regulatory requirements.

[51] GSA (2023) note that change of use of non-residential space with resulting change in lighting requirements is a common occurrence.

For models and monitoring to be suitable for lighting system energy efficiency regulation a number of aspects are needed, some of which are in place and some need additional work. These are described below.

4.10.3.1 Parts which could be tested

Test standards exist and MEPSs are in place for lighting components – light sources and luminaires - in 4E countries.

As described above there are few test standards for sensors – these would need to be developed so that satisfactory performance could be specified. Then these parts could be lab tested and their performance certified as meeting these. The functional requirements for sensors in the California Energy Code could be used as starting points for standard development.

At present there are no test standards for controls, either individually or as part of a lighting system. There are the voluntary specifications for Networked Lighting Controls described above. It is possible that these could be developed into formal standards.

The energy use of sensors and controls is generally low so there may be issues in some 4E jurisdictions with justifying MEPSs to apply to these. (This should not be a barrier in the EU where the legislation which sets the framework for MEPSs, the Ecodesign directive (European Commission 2009), covers energy related products, that is products which do not use energy themselves, but which affect energy use). While having MEPSs in place for all the parts in a lighting system would be the most robust option if this is not possible this need not inhibit setting MEPSs for lighting systems; provided there are test standards the lighting standard regulation could specify the minimum performance for each part. The US walk in cool room regulation provides a precedent for this approach as it sets performance requirements for each component as well as the complete system.

There is a standard for bi-directional digital communication between lighting control products, IEC 62386, and parts can be certified to this standard.

Standard for aspects of lighting systems have been developed or are being developed by ANSI Lighting Systems Committee (C137) (see Section 3.2.5). These could be adopted as is or extended or adapted to provide standardised approaches to different aspects which systems could then be certified to.

4.10.3.2 Accessible databases of parts

Populating models with is parts is made much easier if there are publicly accessible databases which list their parameters. There are some existing databases of lighting system parts:

- the DALI Alliance Product Database which lists all products meeting the DALI-2 protocol
- The listing of equipment certified as meeting the California Energy Code on the California Energy Commission Online Resource centre
- Many 4E countries require appliances or components which have MEPS to be registered and for their performance data to be publicly accessible so if parts have MEPS then this information should be available.

If the data are not already available, then it may be possible for regulations to require that parts be listed on the public database; this is the case in the US for components of WICRs.

4.10.3.3 Certifying lighting models

There are many lighting models available of varying levels of complexity and sophistication as described above. Some of these are used to voluntarily to demonstrate compliance with building regulations in 4E countries as outlined in Section 3.6.

Lighting models will be required by lighting system regulations in order to account for the effect of daylight, room conditions and controls. If they are used, they would need to be certified or validated as fit for purpose for the regulation. In the case of building regulations models are run on a series of standard cases; if the results agree within agreed limits the models are considered valid. A similar approach has been used for lighting models and a standard exists for validation: CIE 171. However, there are limitations to this standard and it seems to the authors that this method would need to be improved to be robust enough to be used in regulations.

4.10.3.4 Formalising and certifying acceptance testing of lighting systems

There is an existing standard, ANSI/IES LP-8-20 The Commissioning Process Applied to Lighting and Control Systems. It is not known how this relates to the acceptance testing required by the California Energy Code. Either the ANSI standard or Californian acceptance procedure or both could be used as the basis of a standard used to certify acceptance testing of a lighting system.

The Californian Energy Code system of certifying acceptance testers could be used as a model for a system for certifying acceptance testers. Another example in a different but related field may be the requirement in many 4E countries for technicians who deal with fluorinated gases to be certified for handling them in different ways (handling, working with stationary refrigeration, air conditioning and heat pump systems).

4.10.3.5 Certifying lighting systems for use for energy monitoring

Monitoring lighting system energy use is necessary for MEPS to be robust both initially and over time. There are two aspects to this: metering energy use and measuring light levels. Lighting energy systems can be designed to fulfil both functions without needing additional sensors or features as demonstrated in the research by Brown et al (2020). However there needs to be a mechanism to check that they can do this sufficiently accurately and certify them as fit for purpose. Further research and engagement with the industry will be needed to achieve this. It is possible that there are precedents in other countries and/or systems that have not come to light during this research which may be useful in developing such certification.

4.10.3.6 Initial certification of lighting system using modelling and monitoring

Once the lighting system has been acceptance tested the systems needs to be certified as meeting the regulatory requirements using modelling and monitoring. This should include a period of monitoring which is long enough to cover a usual cycle of use – that is in workplaces at least one week. The monitored energy use should then be compared with the certified model output. If the two values agree within the regulation tolerance, then the system is compliant with the regulation. If not then the owner/operator needs to use the monitoring information to adjust the system and then monitor for an additional representative period. An external, qualified, certifier is required to check the model and monitoring comparison, and that the system meets regulatory requirements.

4.10.3.7 Periodic certification of performance via modelling and monitoring

There needs to be a requirement and protocol to certify that lighting systems continue to meet regulatory requirements. This would need to be when changes are known to be made to the lighting system. The types of changes may be:

- directly related to the lighting system, such as new luminaires or controls
- or due to changes in the building for example fitting external blinds, moving internal partitions
- or changes in building use – rooms used for different tasks or changes in operating hours.

Not all changes may be noted by the building manager/occupants, so it is suggested that performance certification when there are known changes is supplemented by periodic reporting, say once every two years. As for the initial certification the model and monitoring data for the overall period are compared against each other and against the regulatory requirements. If the values don't match within tolerance or are not compliant then the system needs to be modified followed by monitoring for a representative period. As for the initial check an external, qualified, certifier is required to check the model and monitoring comparison, and that the system meets regulatory requirements.

5 Case study: compressed air systems

5.1 Compressed air system parts and interactions

Compressed air systems are designed to deliver compressed air to machinery, tools, and equipment for a wide range of purposes, including operation, cooling, and control systems. A comprehensive understanding of these systems is needed for optimal design, operation, and maintenance. The system is divided into three subsystems, supply, distribution and end use.

This section describes the different parts, how they interact and what affects their energy efficiency, stating with an overview and then describing each element separately.

Inefficiencies can be grouped into supply and demand:

- How efficiently the compressed air is being supplied by the compressors as shown in Figure 2
- How efficiently the air is distributed (as shown in Figure 3)
- How the minimum and maximum system air pressure and air flow rates have been set by the operator.

Efficiency varies widely between systems; Trianni et al (2020) characterised the scale of energy savings and payback time of numerous efficiency interventions from case studies in the US DoE compressed air scheme. These are used to indicate the scale of the losses that occur throughout the system (Figure 1).

There is also no accepted metric for overall efficiency of a CAS. Benedetti et al (2017) proposed an efficiency metric on a per industry basis comparing energy used for CAS as a percentage of the total energy consumed. For example, CAS consumed 4% of total energy in the average paper manufacturing plant surveyed, and used 18 kWhe CAS per ton of paper produced. However, this is a high-level metric and unsuitable for this work.

Figure 2: Schematic of energy losses in supply system

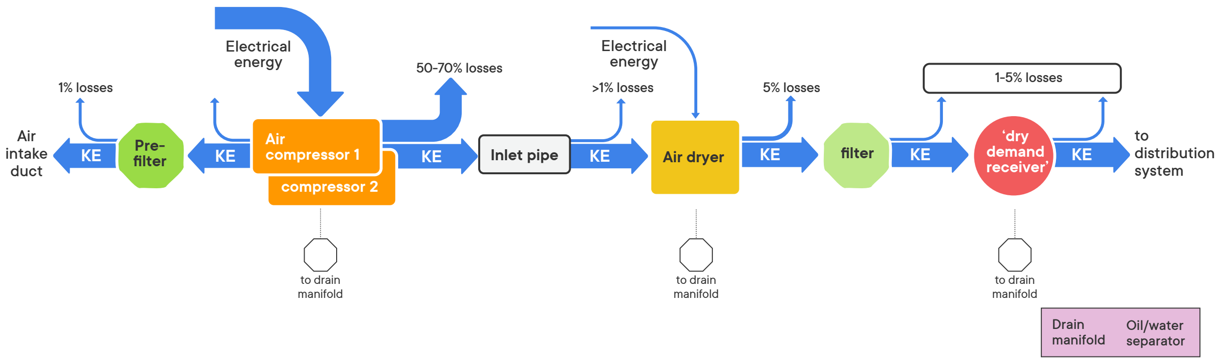
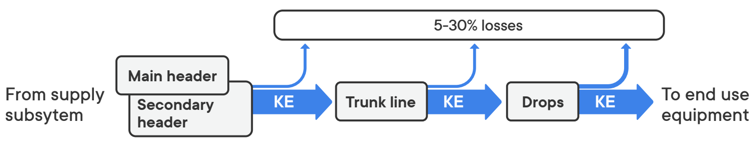


Figure 3: Schematic of energy losses in distribution



5.1.1 Supply

The supply side of a compressed air system encompasses the equipment responsible for generating and treating compressed air before its distribution. The core component of the supply side is the compressor, which is tasked with increasing the pressure of air by reducing its volume. Compressors are available in various types, each suited for specific applications and requirements. Multiple compressors can be used to cope with the demand variability and provide redundancy.

5.1.1.1 Air compressor

The air compressor is the main energy using part. This draws in external air and compresses it, converting electrical energy into useful potential and kinetic energy carried by the airflow mass. This is the main energy losing component since the compression generates large amounts of heat and causes water vapour to be condensed out of the air when it cools again.

An efficient compressor has an isentropic efficiency[52] around 70%-85%, however the efficiency also includes the unwanted heat generated in the compressed air. Typically, less than 50% of the electrical energy is converted into useable kinetic pressure and energy for the system.

Inefficiencies in compressors often arise from outdated or poorly maintained equipment. This is primarily a component efficiency problem. Compressor efficiency is also affected by the intake air; contaminated air can damage the compressor and require more inlet air filtration. Hot and humid air requires additional cooling and drying after compression. In addition, the altitude will affect the air density and require a higher compression ratio.

5.1.1.2 Air compressor controls

For single air compressors there are four main control strategies.

Start/Stop Control is straightforward and typically used in smaller systems or with reciprocating compressors. The compressor starts when the system's air pressure falls below a predefined threshold and stops once the pressure reaches the upper limit. This method is simple but can lead to frequent cycling of the compressor, which might not be ideal for larger systems due to wear and energy inefficiency.

Load/Unload Control allows the compressor to run continuously while managing its load to maintain system pressure. When the demand is low, the compressor unloads, meaning it keeps running but doesn't compress air, thus saving energy compared to starting and stopping. This strategy suits larger systems where constant air supply is needed, but it can be less efficient than other methods if not paired with proper storage and demand management solutions. Unload differs from stop because the motor continues to spin. Compressors can also be set to enter stop after a predetermined amount of time in idle.

Modulating Control adjusts the compressor's output to match the system demand by varying the inlet valve position or the motor speed. This method can provide very stable pressure control but at the cost of reduced efficiency under partial load conditions, as the compressor may run less efficiently when not at full load.

Variable Displacement Control alters the compressor's capacity by changing the active cylinder space without varying the motor speed. It's a more energy-efficient method of matching demand compared to modulating control, suitable for applications where demand varies significantly but does not drop to levels that would make load/unload control more efficient.

Variable Speed Drive (VSD) is a sophisticated control method that adjusts the motor speed of the compressor to vary its output according to demand. This strategy offers significant energy savings, especially in systems with fluctuating demand, by ensuring the compressor operates efficiently across

[52] the efficiency of a thermodynamic process taking place in a theoretically perfect, reversible adiabatic (isentropic) manner

a wide range of conditions. VSD can drastically reduce energy costs and is considered one of the most efficient control strategies for compressors.

For multiple compressors, a **master control system** is used to stage the individual air compressors, ideally with maximum efficiency. Two primary approaches include controlling based on static (absolute) pressure and dynamic (differential or flow-related) pressure measurement.

Static (Absolute) Pressure-Based Control

Static pressure-based control systems monitor and regulate the pressure within the compressed air system at a fixed point, typically within the air receiver or main distribution line. These systems adjust compressor operation based on the absolute pressure readings, aiming to maintain a target pressure setpoint. Depending on whether the pressure is above or below the setpoint, the controller will start or stop compressors, or adjust their load, to maintain the desired pressure level.

This type of control is straightforward and effective for systems with relatively constant air demand or where precise control over air pressure is critical. However, it may not be the most energy-efficient option for systems with highly variable demand, as it doesn't account for the dynamic changes in air flow or pressure drops across the system.

Dynamic (Differential or Flow-Related) Pressure Measurement Control

Dynamic pressure-based control systems take into account the pressure changes caused by air flow through pipes, filters, and dryers, adjusting compressor operation to maintain optimal pressure at the point of use, rather than just at a central point. These systems can measure pressure differentials across the system or monitor flow rates to more accurately match compressor output to demand. By measuring pressure losses or flow rates in different parts of the system, the master controller can make more informed decisions about which compressors to run and at what capacity. This allows for more precise control over the pressure at the point of use, reducing energy consumption by minimizing over-pressurization and the associated energy waste and is particularly beneficial in complex systems with long distribution lines, multiple points of use, or significant fluctuations in demand.

Combining Static and Dynamic Control

Many advanced master control systems integrate both static and dynamic pressure measurements to leverage the strengths of each approach. By monitoring both absolute pressure and flow rates or pressure differentials, these systems can provide a comprehensive view of system performance. This enables more nuanced control strategies that can adapt in real time to changes in demand, system configuration, or operational conditions, leading to optimal efficiency and reliability across a wide range of operating scenarios.

Ineffective control systems for compressors can lead to frequent stop-start cycles, causing multiple compressors to run simultaneously and "fight" against each other. This condition not only compromises system stability but also escalates energy consumption by as much as 50%.

5.1.1.3 Air treatment

Following compression, the air undergoes several treatment processes to ensure its quality and suitability for end-use applications. This treatment typically involves moisture separators, aftercoolers, and filters. Aftercoolers reduce the temperature of the compressed air, condensing water vapor and facilitating its removal. Driers remove moisture from the air, which is crucial to prevent water condensation in the distribution system and at end-use points, which can lead to equipment corrosion and operational issues. Aftercoolers and driers also consume some energy, around 10% of the air compressor. In addition, condensate management is needed to remove oil and condensate that might still form even after drying throughout the supply and distribution system.

Filters are also a critical component of the supply side to remove particulates, oil vapours, and other contaminants from the compressed air. This step is essential to protect downstream equipment and ensure the quality of air for specific applications.

Air treatment components introduce pressure drops in the system. Proper sizing selection and maintenance of such equipment are essential to strike a balance between air quality and minimising pressure drops. Air receivers, while valuable for improving efficiency by stabilizing pressure and enabling the operation of smaller compressors, can also contribute to inefficiencies if not appropriately sized and maintained. Sizing of air treatment includes the size of the inlet pipes and headers to the equipment. Constrictions can cause additional pressure drops.

5.1.1.4 Air receivers

Supply receivers (or air tanks) are used to store compressed air, providing a buffer to accommodate demand fluctuations and stabilise system pressure. This storage capability is vital for maintaining consistent supply under varying operational conditions. General receivers can also be located in the distribution subsystem and immediately before a piece of end use equipment that might have unique supply requirements (generally very high air demand for short periods).

5.1.2 Distribution

The distribution system is responsible for transporting compressed air from the supply side to the points of use. It starts at the main header and comprises pipes, valves, and junctions, designed and arranged to minimise pressure losses and ensure efficient and reliable delivery of air.

Pipes are selected based on material, size, and layout considerations to optimise flow and reduce pressure drops. Valves control the flow and direction of compressed air, allowing for system isolation and regulation as needed. Junctions facilitate the branching of the distribution system to various parts of a facility, ensuring that compressed air is accessible where it is needed.

The **Inlet Pipe** is where the compressed air enters the system from the compressor or compressors. The inlet must be sized correctly to handle the flow from the compressor without causing excessive pressure drop. It's also the point where air treatment components, such as filters and dryers, are typically installed to clean and dry the air before it enters the distribution system.

The **Main Header** is a large pipe that runs the length of the facility and distributes air from the inlet to various parts of the system. It is essentially the backbone of the compressed air system and is sized to minimise pressure drop while delivering the necessary volume of air to all points of use.

The **Secondary Header:** in larger systems, secondary headers may branch off the main header to supply specific areas or types of equipment. These are typically smaller in diameter than the main header but still need to be sized to deliver sufficient air with minimal pressure loss.

Trunk Lines are the major distribution lines that branch off the headers to different sections of the facility. Trunk lines carry compressed air from the headers to closer to the points of use, where smaller distribution lines or drops will take over.

Drops are the vertical pipes that deliver air from the trunk lines or headers down to the individual points of use, such as machines, tools, or workstations. Drops can include valves, regulators, and connectors to control and connect the air supply to the equipment.

Other Components:

Filters, Regulators, and Lubricators (FRLs): These are often installed at various points in the system, especially near points of use, to ensure the air is clean, at the correct pressure, and, if necessary, lubricated before it reaches sensitive equipment.

Drains are installed at low points in the system to remove any accumulated condensate, which can cause corrosion and damage if not properly managed.

Isolation Valves: allow sections of the system to be isolated for maintenance or in case of a leak, without needing to shut down the entire system.

The design of the distribution system is critical to the overall efficiency of a compressed air system. Proper sizing, layout, and material selection are essential to minimize energy losses and ensure reliable operation. Sources of energy loss in the distribution system are:

5.1.2.1 Air Leakages

Air leakages are prevalent in compressed air systems and can range from 5-10% in well-maintained systems to 20-30% in poorly managed ones. These leaks not only increase air consumption but also necessitate increased compressor operation to maintain system pressure. The result is a substantial waste of energy and increased operational costs. Air leaks can occur anywhere in the system, particularly between pipe connections and junctions, and the connection between the end-use equipment and drops.

5.1.2.2 Distribution Losses

Inefficient distribution systems are another source of inefficiency which causes the pressure to drop from the compressor to the end equipment. Any pressure drop means the air must be supplied at a higher pressure to ensure the correct working pressure for the equipment. Undersized (narrow) pipework is a major cause of pressure drop because air flow rates must be higher. Other common design problems include using trunk and branch pipework instead of a distribution loop and installing tight bends which cause friction and turbulence.

Poorly designed distribution systems can also lead to pressure instability, rendering compressors and controls unable to operate efficiently. If the pressure across the system is uneven higher pressure must be supplied to the entire system to meet the required pressure at low points, leading to an increase in energy consumption.

Finally, poor maintenance can also lead to condensates and oil collecting which can block or restrict pipes and cause corrosion which results in a rough internal pipe surfaces that increases friction further.

5.1.3 End-Use

The end-use component of compressed air systems refers to the machinery, tools, and processes that utilize the compressed air. The uses are split into three categories:

Power: The air is used to drive a piece of equipment, e.g. power tools, conveyors and pneumatic lifts

Process: the air itself is being used, e.g. aeration in a water treatment plant.

Control: The air is used to trigger a process, e.g. pneumatic switches.

The efficiency and effectiveness of compressed air as a utility at the point of use are significantly influenced by the design and maintenance of the supply and distribution components. End-use applications dictate the quality and pressure requirements of the compressed air, guiding the selection and design of the supply and distribution components. Oversupply of air, particularly too high pressure, can result in major inefficiencies.

Worn and inefficient equipment consumes more compressed air and energy, leading to increased operational costs. Additionally, improper equipment selection and usage can exacerbate inefficiencies by mismatching air requirements with equipment capabilities.

5.1.4 Energy savings and major system aspects and parts of interest

The main savings available in a CAS are from:

- Eliminating inappropriate uses of compressed air

- Stabilising system pressure
- Exploring lowering pressure requirements of end uses
- Minimising compressed air leaks
- Providing compressed air of appropriate pressure and quality for manufacturing processes.

5.2 Specifying compressed air performance requirements

The compressed air performance requirements describe the air quality, air flow mass and air pressure needed to operate the end use equipment. The end use equipment specifications will describe the requirements, but total air demand will depend on how the equipment is operated. In general, the system will be designed to cope with the equipment with the most demanding requirements, although additional demand side filters, receivers etc can be installed for very specific use cases.

ISO 8573-1:2010 is used to define air purity classes and set air quality requirements.

The main source of calculations described are from the Compressed Air Gas Handbook published by the Compressed Air and Gas Institute (CAGI 2016-2022).

The steady state air demand is calculated based on the sum of the equipment air consumption at 100% performance x load factor. The equipment air consumption is based on typical values or equipment manufacturer data. The load factor is estimated based on the time in operation and the fraction of 100% power output required while in use. Estimating the load factor is application specific and it is recommended values from a similar manufacturing facility are measured and used. For example, the load of a drill will depend on the material being drilled, the thickness of the material, the size of the hole being drilled, and the number of holes. Similar assessments would have to be repeated for every piece of equipment and experience is important in applying the guidelines effectively.

Crucially this does not estimate air variability which is essential to carry out dynamic modelling of the air supply.

Auditing is often recommended to establish the dynamic demand. This involves installing temporary or permanent pressure, flow rate and power sensors into the CAS for a sufficiently long period of time to capture the normal pattern of use, typically two weeks. Auditing is also used as an opportunity to assess and reduce demand. However, auditing is not applicable for new systems or system upgrades where estimates are still required.

Given that estimates are hard to make accurately, and that CAS are often upgraded, oversizing is common. This places greater emphasis on efficient controls and monitoring.

5.3 Testable Parts and standards

This section describes existing test standards and performance standards for parts of a CAS.

5.3.1 Air compressors

Two 4E countries have MEPS for air compressors: China and the US. These are described below.

5.3.1.1 China test standard and MEPS

GB 19153-2019 establishes different efficiency grades and MEPS for displacement air compressors. The test method is described within the regulation, GB 19153-2019, and requires the air flow volume (m^3/min) and power (kW) to be tested against GB/T 3853.

The compressors subject to China regulations include:

- Oil-injected rotary compressors with drive motor power of 1.5-630 kW and exhaust pressure of 0.25-1.4 MPa

- Variable speed oil injected rotary air compressors with drive motor power of 2.2-315 kW and exhaust pressure of 0.25-1.4 MPa
- Reciprocating piston air compressors with drive motor power of 0.75-75 kW and exhaust pressure of 0.25-1.4 MPa
- Oil-free reciprocating piston air compressors with drive motor power of 0.55-22 kW and exhaust pressure of 0.4-1.4 MPa
- Directly driven portable reciprocating piston air compressors.

An equation is used to calculate the specific power, expressed in kW/(m^3/min). Specific power requirements for each efficiency level are tabulated in the regulation, with the values depending on the type of compressor, number of stages, cooling method, drive motor power and working pressure.

5.3.1.2 US test standard

The test procedure for determining compressor energy efficiency under these regulations is codified in 10 CFR 431.344 and appendix A to subpart T of part 431. The test standards were established through a final rule published on January 4, 2017 (82 FR 1052).

The final rule also established that while the large majority of air compressor sales were small, hobby devices, energy consumption is mostly in large air compressors. This justifies the focus on larger compressed air systems for this study as well.

5.3.1.3 US MEPS (Energy Conservation Standard)

The U.S. Department of Energy (DOE) regulations apply to specific types of compressors. The compressors subject to DOE regulations include:

- Air compressors that are rotary compressors
- Compressors driven by brushless electric motors
- Lubricated compressors
- Compressors with a full-load operating pressure within the range of 75-200 psig[53]
- Compressors that are not designed and tested as liquid ring compressors.

An equation is used to calculate the isentropic efficiency MEPS taking into account the pressure and capacity of the air compressor.

The effective date of the most recent final rule for air compressors, 85 FR 1504, is March 10, 2020 Compliance with the new standards established for compressors in this final rule is required on and after January 10, 2025. The previous ECS, 81 FR 79991, was effective December 15, 2016.

5.3.2 CAGI voluntary performance verification and reporting of air compressors.

CAGI operates a voluntary Performance Verification program for reporting the performance and efficiency of compressors. Most of the large manufacturers active in the US market appear to participate. The information is provided in a standardised “data sheet” and requires third party testing. However, the data sheets are held on manufacturer websites and there is no centralised database of the information or API to access the information easily.

5.3.3 Filters and Auxiliary equipment

These are passive equipment to improve air quality and do not consume electricity directly (except air driers) but can reduce efficiency.

[53] 517 to 1379 kPa

Air filters are selected using ISO 8573 (described below). Their performance depends on the equipment and the filtration media. The performance information includes:

- Pressure drop (according to ISO 12500)
- Filtration efficiency (according to ISO 12500)
- Max pressure and inlet capacity flow rate
- Standard/reference operating pressure
- Service life – time/operating hours or pressure drop increase.

To maintain efficiency, the auxiliary equipment needs to be appropriately sized for the maximum system load, or future loads. There is no energy efficiency penalty for oversizing the auxiliary equipment, only a capital cost.

ISO 7183 *Compressed-air dryers — Specifications and testing*, identifies test methods for measuring dryer parameters that include the following:

- pressure dew point;
- flow rate;
- pressure drop;
- compressed-air loss;
- power consumption;
- noise emission.

5.3.4 Other – safety and air leakage testing for pressure vessels and pipework

Many regions have safety requirements which includes larger air receivers and pipework. These include design requirements, (visual) inspection and pressure leakage testing, and specify the frequency of testing and certification. Efficiency requirements could be integrated into this process although the EU Pressure Equipment Directive is clear that it is "limited to the expression of the essential safety requirements" and to minimise the administrative burden.

5.4 Untestable parts and modelling

5.4.1 Untestable parts and modelling – air supply subsystem

5.4.1.1 Dynamic Modelling of air supply, and controls

Air supply performance can be modelled based on the estimated or measured demand of the system. These are many similar calculations for estimating energy consumed based on measured values of air compressor power and use profile (e.g. Schmidt and Kissock, 2004), where total energy consumption = power * time spent by each compressor and each compressor operating mode.

This is used to estimate savings from changing control scheme, fixing leaks and air saver nozzles by calculating reduction in air demand. These are 'ideal' calculations which apply the laws of thermodynamics and assume air behaves as a perfect gas (i.e. ignoring humidity and condensation).

More sophisticated formulae have been described, such as in Young, JT (2016) which includes corrections for inlet air temperature, humidity and polytropic[54] efficiency of the air compressor. CAGI also describe formulae and input values to calculate the air compressor performance required to account for atmospheric pressure, temperature and humidity.

5.4.1.2 Dynamic modelling of air receivers

Air receivers stabilise air pressure and reduce the rate at which the pressure drops in response to a

[54] The real efficiency of a compressor cf isentropic efficiency

demand event. Calculations for sizing the receiver are given based on the air flow rate, pressure and time of the event, taking into account atmospheric pressure are found in the CAGI Handbook (CAGI 2016-2022). However, again this depends on the accuracy with which the event demand is estimated, which could also change over time.

5.4.1.3 AirMaster+

This model has been developed for US DoE to be used by trained auditors to audit CAS. The model allows the basic system characteristics to be input including the estimated, or preferably measured system air supply and pressure, and to predict the effect of changes to the system including:

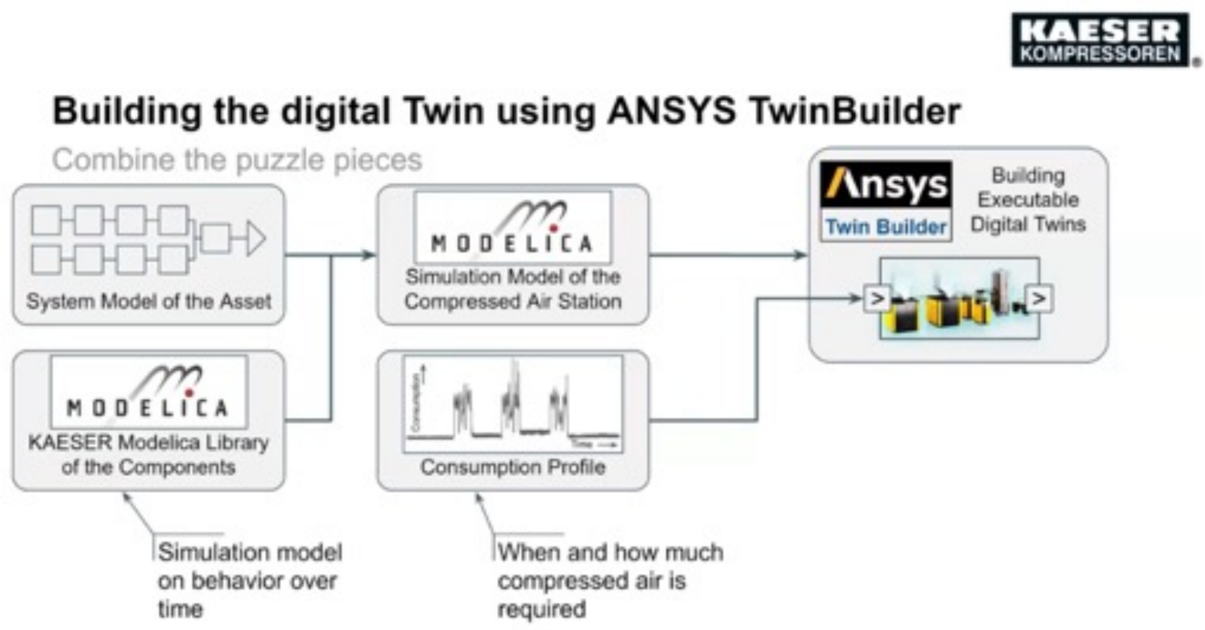
- New, rightsized supply equipment
- Improved controls
- Reducing leaks and artificial demand
- Reducing air supply pressure
- Energy (heat) recovery.

The model is intended to be used as a decision tool and give an estimate of energy and cost savings from various interventions which are sufficiently accurate to enable cost effective changes to be made to a CAS.

5.4.1.4 Compressed air manufacturer tools

Compressed air manufacturers can model the performance of packages of air compressors based on the estimated or measured demand. There is limited information available on these, but Kaeser presented their model in a short presentation available online (Kaeser 2020). This is described as a models,based system engineering approach. There is a two-step approach, first modelling the compressed air station and then the system, shown schematically in Figure 4.

Figure 4: Schematic of the Kaeser compressed air model system



The internal model of the compressed air station is created in 'Modelica' software, from a library of components and a system model of the compressed air station which show the components fit together. The library holds details for current, outdated and competitor components. The model is described 'as not very detailed', but needs around 20-30 (max 80) components to build the model of the compressed air station. This is fed into ANSYS Twinbuilder.

ANSYS Twinbuilder software creates a digital twin of the system used for design and realisation. The model of the compressed air station is combined with a 1-2 weeks of air consumption profile data to simulate the system behaviour and predict performance in terms of how pressure varies and how and when the compressors switch on and off. This can be interpreted by engineers to optimise the compressed air station, but does not appear to estimate energy consumption.

Kaeser stated that future plans were to use the model for Intelligent Asset Management (predictive maintenance and engineering insights) using IoT and sensor data. This could also be used to model, for example, What-if scenarios.

5.4.1.5 Observations

Despite the wide range of uses and the dynamic nature of the use, it should be possible to create a model to estimate the maximum achievable efficiency for any given requirement based on available compressors. This would be based on pressure, flow rate and variability. A MEPS could be set against this, e.g. 20% lower than the maximum, however more data would be needed to assess in reality how close to the optimum a system can operate.

5.4.2 Untestable parts and modelling - air distribution subsystem

5.4.2.1 Steady state modelling of distribution losses

The Compressed Air Gas Handbook (CAGI 2016-2022) describes general rules of thumb calculations to estimate the pressure drop in distribution systems. It presents equations and tabulated input values for:

- Pipe diameter and pressure drop caused by friction per length of pipe and flow rate
- Typical Pressure drops for standard screw pipe fittings e.g. elbows, valves (often expressed as equivalent pipe length).

However, there are no calculations for:

- Overall distribution layout and junctions (requires CFD)
- Pressure fluctuations.

5.4.2.2 Computational Fluid Dynamics

CFD can be used for design validation and troubleshooting of distribution system performance by calculating:

Flow Analysis

CFD allows engineers to simulate the flow of compressed air within the system. By creating a digital model of the system, including pipes, valves, and other components, CFD software can calculate the velocity, pressure, and temperature distribution of the air throughout the system. This analysis helps in identifying potential flow issues such as pressure drops, turbulence, and areas of recirculation.

Pressure Drop Calculation

One of the primary applications of CFD in compressed air systems is to calculate pressure drops along the distribution network. CFD can accurately predict how the pressure varies from the compressor outlet to the end-use equipment. Identifying high-pressure drop areas helps in optimizing pipe sizes, eliminating bottlenecks, and ensuring that the required pressure is maintained at critical points in when designing the system.

Heat Transfer Analysis

Compressed air systems often generate heat during compression. CFD can model heat transfer within the system, including the effects of aftercoolers and heat exchangers. This analysis is needed to understand temperature profiles and ensuring that the air remains at the desired temperature for specific applications.

Leak Detection

CFD can assist in identifying air leakages within the system. By simulating the expected airflow and pressure, deviations between the measured and predicted values can indicate the presence and location of leaks, helping to target maintenance and energy-saving efforts.

Use of CFD in improving the performance of CAS have been reported in Septano et al (2024) and Saadat et al (2016).

5.4.3 Untestable parts and modelling - End-use

Compressed air simply provides kinetic energy. It can be used in almost any application where an electric motor might be found. In addition, CAS can be used for actuation (analogous to an electrical switch) or the air can be used in the process, e.g. drying or aeration. Some of these have wider applications or are specific to an industry. Within a single system there can be a mix of all these applications and achieving sufficient coverage of end-uses in a model or for this research does not seem practical.

The CAGI handbook includes 60 pages covering examples of applications and industries or compressed air uses including:

- Pneumatic tools, e.g. air drills, grinders
- Conveyance belts
- Paint sprayers
- Blast cleaners
- Aeration and agitation of liquids
- Pumping and vacuums in agriculture
- Amusement park rides
- Drying and blowing
- Yarn entanglement.

Of these examples, pneumatic tools (and air motors) seem to be the most widely used and could be a starting point for modelling end-uses. However, as described in Section 5.1.3 demand can vary for a given tool and the efficiency can vary with rotational speed and torque.

5.4.4 Untestable parts - End to end model development

Thabet et al (2020) proposed a model to couple demand and supply by combining existing models and implementing them in MatLab. It models a single air compressor in load/unload mode, air cooler, filtration, storage tank, pipes and a single pneumatic tool. This is a very simple model, and future work is planned to validate the model and increase the complexity of the model. This is therefore not suitable for policy and a usable model is therefore not considered to be available in the short-to mid-term. This is also part of the preparatory work to research the use of AI/digital twins management using real time monitoring.

5.5 Monitoring

Monitoring of compressed air systems can be used to track performance, energy use and identify maintenance issues. These can all help to inform the efficiency of the operation. Common advice, including from CAGI, is to create a performance baseline against which optimisation can be measured and potential maintenance issues identified. This guidance on sensors is taken from CAGI (2016-2022).

5.5.1 Types of Sensors and Placement

5.5.1.1 System performance and air quality

Four different types of sensors can be used:

Flow Meters: Essential for measuring the air flow rate. Recommended placement includes the compressor output and key distribution lines to assess demand and usage efficiency.

Pressure Sensors for tracking system pressure. Installed at the compressor output, post-air treatment stages, and critical usage points to maintain correct pressure levels and identify pressure drops. Additional pressure sensors can be used at end equipment to signal inefficiencies or maintenance issues.

Temperature Sensors: Vital for monitoring air temperature, particularly at the compressor outlet to detect inefficiencies or potential issues. Also suggested before and after air dryers for optimal air treatment.

Humidity/Dew Point Sensors: Measure moisture content in the air, critical for dry air applications. Placement after air dryers is recommended to ensure air dryness and monitor dryer performance.

5.5.1.2 Power and energy

Energy Meters: Direct measurement of the energy consumption of the compressed air system as a whole. Measuring energy use of the compressor as well will aid in assessing overall system efficiency.

5.5.1.3 Maintenance only

Leak Detection Sensors: Ultrasonic leak detectors, though not permanently installed, are a common option for periodic inspections to identify air leaks, a common inefficiency source. Ultrasonic sensors are typically handheld devices that are pointed at the pipework from a distance and used to sweep the entire CAS. Other leak detectors exist with varying levels of ease of use and capabilities for detecting very small leakages.

Vibration Sensors can detect unusual mechanical vibrations, indicating potential issues. Placement on the compressor and mechanical components is advised.

5.5.2 Logging and analysis tools

Central management systems with data loggers for real-time analysis and trend monitoring are used for comprehensive system oversight Sanders et al (2018) proposed combining AI analysis of sensor data with knowledge management to reduce energy losses of CASs. This concept has been tested in research (Sanders et al 2020 and Thabet 2022) but does not appear to have been commercialised yet.

5.6 Policies and applications of modelling and monitoring

Policies for CAS in 4E countries are generally part of a suite of programmes offering support to industry on energy efficiency.

The only CAS regulations on the system efficiency in a 4E country that we identified were the California Energy Commission Building Energy Efficiency Standards which includes CAS as a 'covered process'.

5.6.1 California Energy Commission CAS building regulations

The regulations follow a simplified process of that for lighting systems, as described in the lighting case study. There does not appear to be any modelling required to demonstrate the design is compliant.

CASs have to comply if the total combined power of the air compressor(s) is 25 hp (18.6 kW) or more. It covers compressors, distribution pipework and supply and distribution controls but excludes end-use equipment and related controls.

The Code applies to newly constructed buildings, and additions or alterations to existing buildings. It is not clear if changes must be made to existing parts of a CAS if alteration are made to other parts. For example, would an additional distribution pipe require upgrades to the main piping if it results in the air flow velocity being exceeded (see pipe sizing requirements below).

5.6.1.1 Design Requirements

The requirements are (California Energy Commission (2022a):

Compressors: At least one compressor should be fitted with a VSD and air receiver OR sufficient trim capacity and an air receiver. The exact requirements are specified to try to ensure that the system can operate efficiently across a sufficiently wide range of operating conditions to mitigate unnecessary loading/unloading with appropriate controls.

Controls: CAS with three or more air compressors and a total power of 100 hp (74.6 kW) or more must have controls that can choose the most energy efficient combination of compressors based on current demand.

Pipe sizing: Pipes must be sufficiently large to reduce frictional losses with a total pressure drop of less than 5%. Service line piping must be 3/4inch (1.9 cm) or greater. Main piping heading must have velocity of 20ft/sec (6.1m/s) or below at peak conditions. Distribution and service piping must have flow of 30ft/sec (9.1m/s) or below.

Air leak testing: Piping longer than 50 ft (15.2 m) or more adjoining piping must be isolated and pressurised to design pressure and show no loss of pressure for no less than 30min. Shorter pipework must tested and inspected for leaks. (It apparently does not require leaks to be fixed)

5.6.1.2 Monitoring:

CAS with combined power of 100 hp (74.6 kW) or more must measure and log system pressure, power, and total airflow. The trends must be visually displayed for every measurement point and this data must be stored for at least two years.

5.6.1.3 Acceptance testing

Acceptance testing and certification is required, (California Energy Commission 2022c) however, unlike lighting, there is no training and certification scheme for Acceptance Test Technicians. There is a general requirement in the regulation that allows the enforcement agency to verify the person is competent, but it does not specify what this entails.

5.6.2 Audits and technical support

Commercial services exist to help audit compressed air systems and design new systems. These may be offered independently or by equipment suppliers. Auditing is also provided by the US DoE, who train auditors to apply the AirMaster+ tool (Section 1.4.1.3). In North America the Compressed Air & Gas Institute (CAGI) operate a certification scheme for auditors[55].

In New Zealand the Energy Efficiency and Conservation Authority (EECA) offers co-funding for auditing CAS, system optimisation or installing a monitoring and targeting system[56]. Larger energy users can also be co-funded for industrial design advice. The EECA have published a Compressed Air Systems Audit Standard (EECA 2015). This is a standard for the auditing of the energy efficiency of electric motor-powered compressed air systems, aligned with align with AS/NZS3598.1:2014[57] and AS/NZS3598.2:2014[58]. It is designed to guide the collection and analysis of compressed air system data for the purpose of identifying opportunities for improving the system's energy efficiency and providing relevant technically and commercially sound recommendations. EECA has commissioned Carbon and Energy Professionals New Zealand (CEP) to maintain the Audit Standard, in conjunction with relevant industry stakeholders. CEP offer Energy Master Compressed Air Specialist Accreditation based on the audit standard.

55 https://www.cagi.org/training-and-certification
56 https://genless.govt.nz/for-business/on-site/use-efficient-equipment/compressed-air/
57 Energy audits - Part 1: Commercial buildings
58 Energy audits - Part 2: Industrial and related activities

Other standards for compressed air energy audits include:

- Canada C837-16 (R2021) Monitoring and energy performance measurements of compressed air systems
- ASME EA-4–2010 (R2020) Energy Assessment for Compressed Air Systems (The American Society of Mechanical Engineers) – US and reportedly widely used in Asia
- ISO 11011:2013 Compressed air — Energy efficiency — Assessment

Auditing is supported by some modelling or calculations, but it is only effective in combination with expert knowledge. This is partly because the model and calculations often use general rules that might not be applicable in every situation.

Based on the standards above, a full audit process can be summarised as:

- Monitor and assess current demand profile (pressure and air flow changes over hours/days/weeks)
- Assess inefficient/unnecessary demand e.g. blowers, equipment no longer being used
- Assess artificial demand e.g. leaks, narrow pipework
- Determine useful demand requirements (pressure, airflow and air quality)
- Assess current compressor operation
- Determine optimal compressors and operation for useful demand
- Assess costs and savings
- Implement changes to reduce demand and optimise supply.

5.7 Policy considerations

There are no complete, or accurate, models for compressed air, and regulating based on sub-systems and critical performance indicators is the most pragmatic option in the short term. The exemplar (and only example) is the Californian regulations which could be adopted more widely in the short term. This also sets precedent for requiring monitoring, logging and real-time dashboards to view the data.

The one area of weakness, especially in comparison to lighting, is that there are no qualifications needed to complete acceptance testing. Examples of standardised training for auditing are available in the USA and New Zealand which could be adapted. National professional bodies could also be directed to provide this.

5.7.1 Long term policy options

There are no full models for CAS or standard systems which can be used to verify models as is the case for building energy models. A possible long-term policy could be to extend the coverage of test standards for more parts of CASs alongside developing models, starting with subsystem models.

5.7.2 Air supply subsystem model including controls

The compressed air package is the most easily regulated, but requires an estimate of the air demand (section 1.7.5.1). While there are no standardised models for air compressor packages non-standardised models are available. Two options are considered.

- Option 1 create standardised dynamic model
- Option 2 validate existing models.

Develop a way of validating existing models will enable regulations to come into effect sooner and encourage innovation. The risk is that estimates using different models/from different manufacturers will not be directly comparable. To mitigate this, reviews and improvements to the validation process, and as a result the models, should be required in the policy.

Validating models rather than developing models does not require policy-makers to have technical expertise. Digital twin models can be validated using reference CAS designs and input data or using real life monitoring data. Similar approaches are already used for AI/neural network training, (Sanders et al 2020) and are effective if the boundary conditions are well established.

5.7.3 Air distribution system model

Requirements for the air distribution system is to reduce the friction and subsequent pressure drop. The basics can be calculated at component level but not the overall design.

There are several options to address the distribution system design:

- Option 1 CFD analysis
- Option 2 Requirements on pressure drop based on length, junctions and max air demand (e.g. CAGI calculations). E.g. 0.2bar/m requirement
- Option 3 Pressure drop and air speed measurement, similar to current California Energy Code requirements.

CFD analysis would be the most accurate way to estimate the pressure drop created by the design but also the costliest. More in-depth research would be needed to understand if this is cost-effective compared to the other options.

Option 2 while less accurate than option 1 could be used to estimate the pressure drop. The requirements could be based on the allowable pressure drop based on the effective length of the entire system, including junctions. This is effectively a MEPS for the pipework parts and cannot assess the efficiency of the overall design itself. In addition, since it is an estimate, the final design may not match this even if installation is correct. More research may be needed to understand what the tolerance between calculated pressure drop and that measured in the installed system should be.

Option 3 only covers a portion of the pipework but because it is based on the final installed system it guarantees a level of efficiency has been achieved. This option requires acceptance testing.

5.7.3.1 Installation/Operation and maintenance

Installation quality can have a large effect on the pipework. The pipework also requires regular maintenance. Both can be addressed through monitoring, or regular maintenance checks. There are two strands to this:

- Air tightness testing and/or direct leak detection (as described in Section 1.5.1.3).
- Measuring pressure drop initially to establish a baseline and then continuously or periodically to check that pressure drop does not increase excessively over time.

5.7.4 System Monitoring

Monitoring can be used to validate the accuracy of the initial modelling and check the system is optimised.

Sensor requirements can be set using a hierarchy of importance. Because the air flow rate sensors can be relatively expensive, installation can be required based on the size of the CAS and/or as a % of total Capex or a % of total airflow covered.

An example hierarchy of sensors that should be installed in the following order:

- Critical
  - Power at all compressors
  - Pressure at inlet and main header pipes
  - Flow rate from all compressors

- Recommended
  - Flow rate at main header and distribution pipes
  - Pressure at end equipment.

While the monitoring system is normally installed with the new equipment, another option is a regulation that requires a monitoring system to be installed to measure air demand before any upgrade or system change is made. We are not aware of any precedent for this but it could be effective for systems such as CAS where standardising demand is difficult and rightsizing of equipment is important.

MEPS that require sensors to be integrated into the parts instead of placing the responsibility on the installer is another option. This has the potential advantage of ensuring that the sensor is installed in the correct location and calibrated. It also has the potential to lower costs as the B2B supply of sensors is economically more efficient. Some parts, such as air filters and pressure vessels already have pressure sensor integration as an option at purchase.

5.7.5 Maximum and dynamic air demand measurement/estimation

An estimate of the maximum demand is required to ensure rightsizing of air treatment equipment, air receivers, and air distribution subsystem. Maximum demand applies to the whole system rather than individual sections (supply, distribution) and therefore can be measured more easily with less equipment. There are different options with varying costs and benefits:

- Option 1 audit/short term measurement. A measuring period of one to two weeks is generally what is specified in audits, but the length of time required will depend on the manufacturing process and periodicity.
- Option 2 Install permanent sensors with loggers. A flow rate and pressure sensor is approximately 1000 EUR.
- Option 3 Estimate demand using expert knowledge and accepted typical values.

Options 1 and 2 require action at the planning stage of an upgrade. This is unusual but should be possible in a new regulatory framework. Option 3 is the only possibility for new systems, and system expansions but is less accurate, particularly for dynamic demand. Possible ways to mitigate this are:

- Mitigation 1 require detailed calculations and explanations for estimates of air demand and standardised values to be submitted by the regulator (not simply results).
- Mitigation 2 require reporting after period of operation with remedial (cost effective) actions if required.
- Mitigation 3 control system requirements to cover wide range of demand changes.

5.7.6 System design submission with pressure profile

A schematic of the CAS design is required to check the installed system meets all the efficiency and performance parameters. Block diagrams (as used by Kaser and suggested in US DoE audits) provide the basic information for modelling and to graph the pressure profile. The details required include pressure profiles at:

- Inlet to compressor (to monitor inlet air filter) versus atmospheric pressure.
- Differential across air/lubricant separator (if applicable) .
- Inter-stage pressure on multi-stage compressors.
- Pressure differentials, including at:
  - Aftercooler
  - Treatment equipment (dryers, filters, etc.)
- Multiple points in the main header and various distances from the supply inlet, including closest and furthest away.
- Distribution pipes

6 Key findings from the case studies

The overall policy framework would require the following obligations and powers for the Government. Some of these are essential:

- To add a power to regulate changes to existing systems.
- To add a power to require registration/notification of new systems and substantive changes to existing systems.
- Set efficiency and operational requirements on the systems (including models), subsystems and parts.
- Allow on premises inspection of systems by certified actors (may not need to be national inspectors).
- Set monitoring and reporting requirements.
- Impose penalties for failing to register, monitor and report as well as not meeting performance requirements.

The examples found during this review suggest additional powers which would make regulation more effective are:

- Requiring reporting of parts' efficiency in a public database.
- Creating training and certification schemes.
- Creating supporting tools and documentation.

It is not necessary for the powers to be established in a single piece of legislation; they could be built around existing regulation legislative powers and/or added to over time.

Our initial thoughts on the aspects which are most novel for energy efficiency product policy are below.

6.1 Notification/registration

Systems would need to be registered, with a notification process to identify systems that already exist. This should be easier for CAS because the priority is on fewer larger systems that consume the largest proportion of energy. Large organisations operating systems are also easier to engage through industry associations and more likely to comply with requirements to notify. There are several possible routes to CAS registration:

1. Normal communications channels
2. Manufacturers notification of sale of large air compressor
3. Actively identify compressed air systems

which could operate together.

Notification is more difficult for lighting systems because of the large numbers of systems involved. However, most countries will have a registry of all large commercial buildings, their size and information on their owner. As it reasonable to expect that they will all have lighting systems it should be feasible to register all of these within a certain period.

6.2 Parts information availability and database

Regardless of what models are used, the part performance data will be required. Regulators will need to consider how best to make this complete and up to date and how this should be funded. Three options are currently in use:

- Mandatory database of component performance.
- Voluntary/industry association database freely accessible.
- Commercial database accessible to all at a fair cost.

Based on the Kaeser compressed air system example, the database will also need to be populated by old parts to allow system upgrades to be modelled.

6.3 Standardised reporting formats

For CASs air supply and air distribution calculations need input data on the air demand, and the performance of the compressor and air treatment. Standardising reporting formats makes it easier to create databases and models. Standardised reporting of the model outputs and monitoring also makes it easier for review by authorities, possibly with software or AI in the future. This helps to reduce costs and speed up authorisations.

Similar arguments apply for lighting systems.

6.4 Managing additional costs

In the proposed long-term solutions for both case study systems there are three intervention points: design submission, system acceptance following installation and ongoing (or periodic) monitoring. This will result in higher regulator/enforcement body costs than in conventional product policy. One way to address this is to charge the system owner. This approach is common in building regulations, and is used in Australian product policy. It can also act as an incentive for systems owners to ensure the submissions are correct.

There are some ways of reducing costs. For example:

- Not requiring on site checks, which are more expensive, on systems with advanced monitoring and reporting.
- Using video and photo evidence instead of on-site certification.
- Checking only the first CAS and then random checks if multiple CASs are operated on the same site or the same owner.

6.5 Certifying acceptance testers

The proposed approaches require certification of acceptance tester. In the California model for lighting systems certification is provided by a non-profit organisation as a service. Individuals (or their employers) pay for the training and certification; they recover this cost from charging for certification. This relies on there being a sufficient market for these services. An alternative approach would be for the Government to offer training and certification free of charge or, initially at least, to subsidise the cost so that there is a large enough pool of certifiers.

6.6 Non-compliances and proposed mitigations

This approach to regulation will generate new types of non-compliances, requiring new mitigations. These may include:

- A system is found not to be registered. This triggers registration and certification, possibly followed by remediating action to meet the regulatory requirements.
- For CAS if reported sensor readings are outside air demand requirements estimated in the design (particularly too high), or for lighting systems if energy use is too high the system operator is given a fixed time to correct these or provide an explanation and adjust the system model.

- More extreme variation in sensor readings triggers a system audit by a certified third party and audit recommendations must be implemented.

The most challenging type of non-compliance will be where the modelled system energy efficiency meets the regulatory requirements, but the measured performance doesn't. This could be because:

- the model is inaccurate.
- incorrect data has been entered into the model.
- installation quality is poor.
- parts are not performing as required/expected.
- the monitoring is faulty (e.g. inaccurate sensors).
- environmental factors (e.g. temperature, humidity, daylight levels) are outside the expected range.
- or a combination of several of these factors.

A systematic approach will be needed to identify where the error lies before the system can be adjusted to make it compliant. Since the model is validated by the regulator, and the parts supplied by the manufacturer, it must be noted that non-compliance might not be the responsibility of the system owner.

Annex: Additional information on lighting policies and standards

A1.1 EN 15193-1 Energy requirements for lighting

EN 15193-1 is a European standard that specifies the methodology for evaluating the energy performance of lighting systems for providing general illumination in residential and non-residential buildings. It also provides a calculation method for determining the energy requirements for artificial lighting in buildings. The standard can be applied to new, existing, or refurbished buildings.

Key features of EN 15193-1 are:

- A user-friendly methodology: The standard provides a step-by-step approach for calculating lighting energy requirements, making it easy for practitioners to use.
- It considers occupancy and usage patterns: The method takes into account the occupancy and usage patterns of the building, ensuring that the energy requirements are accurately assessed.
- It offers a flexible approach: The standard allows for adjustments to be made based on specific building characteristics and lighting conditions.

The scope of EN 15193-1 is:

- It applies to general illumination; the standard focuses on the energy requirements for general illumination, excluding task lighting, display lighting, and desk lighting.
- It covers residential and non-residential buildings.
- It excludes lighting equipment characteristics: the standard does not address the characteristics of lighting equipment (lamps, control gear, and luminaires).

The benefits of using EN 15193-1 are:

- Improved energy efficiency: The standard helps to identify areas for energy savings in lighting systems, leading to reduced energy consumption and costs.
- Compliance with energy regulations: The method can be used to comply with energy performance regulations for buildings.
- Effective lighting design: The standard provides a framework for designing energy-efficient lighting systems.

The methodology for calculating lighting energy requirements in EN 15193-1 involves three main steps:

1. **Data collection:** This step involves gathering information about the building, its lighting systems, and the occupancy and usage patterns. This information includes:
   - Building characteristics: Building dimensions, floor area, window area, room types, and task areas.
   - Lighting system characteristics: Number of luminaires, light output of luminaires, lighting control systems, and dimming capabilities.
   - Occupancy and usage data: Hours of occupancy per day, hours of lighting operation per day, and average illuminance levels.
2. **Lighting energy calculation:** This step involves calculating the annual lighting energy consumption using a specific methodology. The standard provides three methods for calculating lighting energy requirements:

- Method 1: The most accurate method, based on a detailed lighting scheme design. It requires detailed information about the lighting layout, lamp types, luminaires, and control systems.
- Method 2: A simplified method that uses average lighting power densities for different types of buildings. It is less accurate than Method 1 but requires less input data.
- Method 3: A hybrid method that combines elements of Methods 1 and 2. It provides a balance between accuracy and simplicity.

3. **Energy normalisation:** This step involves normalising the calculated energy requirements to a reference area to obtain a comparable measure of lighting energy performance. The standard uses the Lighting Energy Numeric Indicator (LENI) as the normalization factor. LENI is defined as the annual lighting energy consumption (kWh/m^2/year) divided by the reference area (m^2).

In addition to the three main steps, the standard also provides guidelines for selecting appropriate lighting controls, optimizing lighting layout, and considering daylighting strategies to further improve energy efficiency.

Method 1 in EN 15193-1 is the most comprehensive and accurate method for calculating lighting energy requirements. It is based on a detailed lighting scheme design, which includes the following information:

- Lighting layout: Location and type of luminaires, including their positions, angles, and mounting heights
- Lamp types: Type, wattage, and efficiency of lamps
- Luminaires: Type, light output, and efficiency of luminaires
- Control systems: Type of lighting control systems, including occupancy sensors, daylight sensors, and dimming controls.

Using this detailed information, Method 1 involves the following steps:

1. Calculate illuminance levels in each zone or task area of the building using illuminance calculation methods such as the inverse square law or a lighting software program.
2. Calculate power consumption of each luminaire based on its light output, lamp type, and luminaire efficiency.
3. Determine lighting operation factors for each zone or task area based on occupancy and usage patterns. The lighting operation factor is the percentage of time that the lighting is switched on.
4. Calculate annual energy consumption for each zone or task area by multiplying the calculated power consumption by the lighting operation factor and the number of hours of operation per year.
5. Sum annual energy consumptions: add up the annual energy consumptions for all zones and task areas to obtain the total annual lighting energy consumption for the building.

Method 1 is the most accurate method because it takes into account the detailed lighting design, which can significantly influence the energy performance of the lighting system. However, it also requires the most detailed input data, making it the most time-consuming and resource-intensive method.

Method 2 in EN 15193-1 is a simplified method for calculating lighting energy requirements. It is based on average lighting power densities for different types of buildings, which are provided in the standard. It requires less detailed input data than Method 1, making it faster and easier to use. However, it is also less accurate.

The steps involved in Method 2 are:

1. Select building type according to the standard's classification.
2. Determine the reference area, which is typically the usable floor area.

3. Calculate area-weighted power density for the building type based on the standard's tables.
4. Determine lighting operation factor based on the building type and occupancy and usage patterns.
5. Calculate annual lighting energy consumption by multiplying the area-weighted power density by the reference area and the lighting operation factor.

LENI allowances can be adjusted for daylight to account for the impact of natural light on lighting energy consumption. There are two main methods for adjusting LENI allowances for daylight:

- Daylight Factor Adjustment: This method multiplies the baseline LENI allowance by a factor that is based on the average daylight factor (DF) for the building or space. The DF is a measure of the amount of daylight that reaches an interior space. A higher DF indicates more daylight and therefore less reliance on artificial lighting.
- Daylight-Responsive Controls Adjustment: This method credits buildings for the use of daylight-responsive controls. The credit is typically based on the percentage of time that the controls are effective in reducing artificial lighting use.

Some examples of how LENI allowances can be adjusted for daylight are:

- A building with an average DF of 50% may have a LENI allowance that is 20% lower than the baseline allowance for a similar building without daylighting.
- A building with daylight-responsive controls that are effective for 80% of the time may be able to claim a credit that reduces their LENI allowance by 16%.

By incorporating daylight into the LENI calculation, building owners and operators can more accurately assess the energy efficiency of their lighting systems and make informed decisions about how to optimise their use of daylight.

A1.2 Voluntary specifications for networked lighting control systems

Networked Lighting Controls[59] (NLC) is a voluntary programme which sets minimum functionality specification for lighting systems, in a similar way to the EU smart readiness indicator. This includes the types of sensors, lighting controllability, user interface and control strategies. At the highest level, luminaire level lighting control (LLLC) is recommended which enables each light to be controlled with its own sensors. The main control strategies discussed are:

- **Networking of luminaires and devices:** The capability of individual luminaires and control devices to exchange digital data with other luminaires and control devices on the system.
- **Daylight harvesting:** The capability to automatically affect the operation of lighting or other equipment based on the amount of daylight and/or ambient light present in a space, area, or exterior environment.
- **Occupancy sensing:** The capability to automatically affect the operation of lighting equipment based on the detection of the presence or absence of people in a space or exterior environment.
- **Personal control:** The capability for individuals to adjust the illuminated environment of a light fixture or group of light fixtures in a specific task area to their personal preferences, via networked means.
- **High-end trim (aka "task tuning"):** The capability to set the maximum light output to a less-than maximum state of an individual or group of luminaires at the time of installation or commissioning. LEDs may provide more light than required when new in order to allow for the fact that they dim over time. Trim/tuning may be needed at first and then adjusted over time in response to reducing light levels.
- **Scheduling:** The capability to automatically affect the operation of lighting equipment based on time of day, week, month, or year.

[59] Operated by DLC, https://www.designlights.org/, an independent nonprofit organization

In addition, they have recommended but not yet defined standardising monitoring and reporting of system performance data. The aim of this is to enable better comparison and analysis of data and energy savings between buildings.

NLC also has the potential to auto-configure the most common controls and simplify calibration, e.g. using a tablet to interface with the system while configuring and calibrating the system.

A particular application of NLC is DALI (Digital Addressable Lighting Interface), a protocol (language) for bi-directional digital communication between lighting control products based on IEC 62386 (DALI 2023). The DALI Alliance created and launched a certification program based on the latest version of the DALI protocol DALI-2 in 2017. DALI-2 product test results are verified by the DALI Alliance before certification is granted. Every certified product is publicly listed in the DALI Alliance Product Database.

A1.3 International Energy Conservation Code approach for lighting

The International Energy Conservation Code (IECC) provides two methods for determining the allowable interior lighting power allowance for buildings: the Building Area Method and the Space-by-Space Method.

A1.3.1 Building Area Method

The Building Area Method is a simplified method that is based on the building's gross lighted area and the applicable lighting power density (LPD) for the building type. The LPD is a value in watts per square foot (W/ft^2) that represents the average lighting power consumption for a given building type. The applicable LPD for each building type can be found in the IECC tables.

The LPD using the Building Area Method can be calculated by:

1. Determining the gross lighted area of the building. This is the total area of all spaces that require artificial lighting.
2. Identifying the applicable lighting power density (LPD) for the building type. This can be found in the IECC tables.
3. Multiplying the gross lighted area by the applicable LPD. This gives the allowable interior lighting power allowance for the building.

A1.3.2 Space-by-Space Method

The Space-by-Space Method allows for greater flexibility in calculating the allowable interior lighting power allowance for different areas of the building. It is based on the specific lighting requirements of each space, considering factors such as illuminance levels, task or ambient lighting, and occupancy schedules.

The LPD using the Space-by-Space Method can be calculated by:

1. Identifying the types of spaces in the building.
2. Determining the illuminance levels required for each space. This can be based on recommended illuminance levels for different activities or tasks.
3. Calculating the power consumption of each type of luminaire based on its light output and efficiency.
4. Determining the lighting operation factor for each space, which is the percentage of time that the lighting is switched on.
5. Calculating the annual lighting energy consumption for each space by multiplying the power consumption by the lighting operation factor and the number of hours of operation per year.
6. Summing the annual lighting energy consumptions for all spaces to obtain the total annual lighting energy consumption for the building.
7. Calculating the allowable interior lighting power allowance by dividing the total annual lighting energy consumption by the annual hours of operation.

The IECC also provides additional requirements for specific types of lighting, such as exit signs, emergency lighting, decorative lighting, and task lighting.

A1.3.3 Adjustments for daylight

The IECC recognises the importance of daylighting in reducing energy consumption for artificial lighting. Daylighting is the use of natural sunlight to illuminate interior spaces, which can significantly reduce the need for artificial lighting. The IECC incorporates daylighting into its lighting requirements through two primary methods:

1. Daylight Responsive Controls: The IECC requires the use of daylight responsive controls in certain types of buildings and spaces
2. Daylight Factor: The IECC uses the Daylight Factor (DF) to quantify the amount of daylight that reaches an interior space. The DF is the ratio of the illuminance on a horizontal surface within a space to the simultaneous horizontal illuminance outside the space at a reference point on a clear day. The IECC specifies minimum DF requirements for different types of spaces, encouraging the use of daylight in even the most interior spaces.

By accounting for daylight through these methods, the IECC aims to reduce the energy consumption of buildings while also creating more comfortable and visually appealing indoor environments.

The lighting power density (LPD) can be adjusted by daylight factor and occupancy to account for the impact of these factors on lighting energy consumption. The daylight factor (DF) is a measure of the amount of daylight that enters a building through windows or skylights. The higher the DF, the more daylight is available, and the lower the amount of artificial lighting required. To account for the impact of daylight on LPD, the IECC provides daylight-adjusted LPD tables that specify the allowable LPD for different types of buildings and spaces based on the DF. For example, a retail store with a high DF may have a lower allowable LPD than a retail store with a low DF, as the high DF will reduce the need for artificial lighting.

The occupancy of a building or space also has an impact on lighting energy consumption. When there are more occupants, there is a greater need for artificial lighting to provide adequate illumination for tasks and activities. To account for the impact of occupancy on LPD, the IECC provides occupancy-adjusted LPD tables that specify the allowable LPD for different types of buildings and spaces based on the occupancy schedule. For example, a conference room that is occupied for 8 hours per day may have a higher allowable LPD than a conference room that is only occupied for 4 hours per day, as the higher occupancy will increase the need for artificial lighting.

By adjusting the LPD based on daylight factor and occupancy, the IECC aims to optimize the energy efficiency of lighting systems while still providing adequate illumination for occupants. This helps to reduce the overall energy consumption of buildings and contributes to a more sustainable built environment.

A1.4 Existing building code: ASHRAE 90.1 2022

The IECC is referred to as a model energy code because building codes are state or local laws; there is no national building energy code in the United States. It is updated every three years. For commercial buildings, American National Standards Institute (ANSI) standard ASHRAE 90.1 is considered the model code. It is published every three years with updated requirements; 2022 is the most recent edition.

A1.4.1 Requirements for office lighting

According to GSA (2023) the ASHRAE 90.1 2022 requirements for lighting in an office space are as shown in Table 3.

Table 3: Summary of requirements for office lighting under ASHRAE 90.1 2022 (GSA 2023)

Office Size (ft²)	LPD (W/ft²)	RCR	Multi-level lighting control	Daylight response sidelight	Daylight response toplight	Auto reduction	Auto full off
≤ 150	0.73	8	Required				Required
> 150 and ≤ 300	0.66	8	Required				Required
> 300	0.56	4	Required	Required	Required	Required	Required

150 ft² is roughly 13.9 m², 300 ft² is roughly 27.9 m².

Lighting Power Density (LPD) is defined as watts of lighting per square foot of room floor area (W/ft²)

As reported by Dilouie (2023) changes to the 2022 edition for lighting controls include:

- if the office is 300 ft² or larger occupancy sensors are required to provide automatic shutoff within 20 minutes of the area being unoccupied. The control zone for each sensor is limited to 600 ft².
- New threshold for daylight-response controls: Standard 90.1 requires that general lighting in daylight areas feature daylight-responsive controls that independently control the lighting, with exceptions. It defines the dimensions of these daylight areas based on whether they are side-lit (adjacent to vertical fenestration such as windows) or toplit (under fenestration such as skylights), with side-lit areas divided into primary (directly adjacent to fenestration) and secondary (directly adjacent to primary) areas. The standard indicates a wattage threshold at which automatic daylight-responsive lighting controls are needed to control general lighting in daylight areas. In the 2022 version, if the total wattage of general lighting either entirely or partially in the primary side-lit area is 75 W or greater, daylight-responsive control is required. This threshold was reduced from 150 W in the previous version of 90.1.

Additionally, if the total wattage of general lighting either entirely or partially in the primary and secondary side-lit areas is 150 W or greater, daylight-responsive control is required in both areas, with each area being independently controlled. This was reduced from 300 W in the previous version of 90.1.

For toplit areas, if the total wattage of all general lighting either entirely or partially in a daylight area under skylights and roof monitors is 75 W or greater, daylight-responsive control is required for the area. This was reduced from 150 W in the previous version of 90.1.

In all the above cases, the daylight-responsive control will reduce lighting power in response to daylight using continuous dimming to 20 percent (or less) plus Off. Note that general lighting in overlapping sidelit and toplit daylight areas must be controlled together.

A1.4.2 Lighting alterations

As reported by Dilouie (2023) as 90.1 evolved, lighting retrofits have increasingly become recognised as within the standard's scope. In the new 2022 version, all alterations are lumped together, including retrofits in which the original lamps and driver/ballasts are replaced with lamps and drivers/ballasts that were not components of the original luminaire. These alterations are then broken out and assigned separate requirements depending on whether the lighting is interior or exterior.

If the lighting system in the interior building spaces adds up to more than 2 000 W of load, the alteration must comply with the standard's lighting power allowance and mandatory control requirements that are applicable to each altered space. If the connected lighting load is 2 000 W or smaller, the alteration must comply with the standard's lighting power allowance requirements (or result in new wattage at least 50 percent below the original wattage of each altered lighting system) and then comply with only the standard's manual local and automatic shutoff mandatory lighting control requirements.

A1.4.3Verification and testing

ASHRAE code requires that devices and systems be tested to verify that control hardware and software are calibrated, adjusted, programmed and in proper working condition in accordance with the construction documents and manufacturer's installation instructions.

For example, for daylighting controls to check that:

1. All control devices (photocontrols) have been properly located and field calibrated to set points and threshold light levels
2. Daylight controlled lighting loads adjust in response to available daylight
3. The location where the calibration adjustment is made is available only to authorised personnel

A1.5 EU Energy Performance of Buildings Directive (EU) 2018/844 technical guidelines for establishing and enforcing technical building system requirements

Technical building systems (TBSs) are defined in the Energy Performance of Buildings Directive (EPBD) as 'technical equipment for space heating, space cooling, ventilation, domestic hot water, built-in lighting, building automation and control, on-site electricity generation, or a combination thereof, including those systems using energy from renewable sources of a building or building unit' (Article 2(3) of the EPBD).

The performance of technical building systems has a significant impact on overall building energy performance, therefore, one of the aims of the EPBD is to ensure that technical building system performance is optimised. In particular:

- Article 8(1) requires Member States to set system requirements on overall energy performance, proper installation, appropriate dimensioning, adjustment and control of technical building systems
- Article 8(9) requires Member States to ensure that when a technical building system is installed, replaced or upgraded, the overall energy performance of the altered part or (where relevant) of the complete altered system is assessed

The European Commission commissioned research to establish technical guidelines to help Member States put these provisions into practice; these were published as Van Tichelen et al (2023). The guidelines for lighting systems are described in the following sub sections. The status of these guidelines is unclear; they appear to be discretionary. They would need to be adopted into Member State regulations to be mandatory in each Member State.

A1.5.1 Dimensioning requirements

Article 8(1) requires Member States to set appropriate TBS dimensioning requirements because oversized systems will often operate far from the optimal efficiency level and create unnecessary energy wastage. In practice, this requires obligations to be imposed on system designers and installers to conduct an adequate dimensioning assessment according to specified procedures and to document the outcome. The dimensioning assessment needs to determine the realistic (not overly inflated) maximum load based on the actual characteristics of the building, its occupants, how it's to be used and climate. It also needs to determine the efficiency of the system in delivering that load so it can be sized accordingly.

Dimensioning requirements could be set for new or replacement lighting systems:

For non-residential lighting in indoor workplaces in large buildings (>500 m²) where EN 12464 applies, the following data needs to be provided at the design stage:

- printout (pdf) of the calculated LENI, Power Density Indicator (PDI), performance indicator, parasitic power values including EN 12464 minimum values (e.g. as can be generated by DIALUX etc. software)
- floor plan (pdf) with indication of luminaires, sensors for BACS and major task areas (EN 12464)
- inform the building owner that wall reflection coefficients can have significant impact on the illumination values. Issue a warning for high lighting power demand when the coefficient of reflection is below: 70% for walls, <85% for ceilings and 50% for floors.
- averaged value (LENI, PDI, performance indicator, parasitic power) per submeter area whereby at least one submeter per 200 m² must be assumed. Electrical wiring diagram (1-wire) to show how the luminaires are connected to the LENI submeters
- luminaire data sheets.

For other lighting applications the following data could be required:

- the total calculated luminaire power performance indicator [W/m²]
- the total calculated parasitic power of the lighting circuit with all lights switched off [W/m²].

A1.5.2 Adjustment (installation) requirements

Adjustment requirements could be set:

For non-residential lighting in indoor workplaces within large buildings where EN 12464 (>500 m²) applies, the following data would be needed:

- a declaration of honour from the installer that all luminaires and sensors are installed according to the plans (see dimensioning requirements in the previous subsection).
- a checklist for BACS lighting functions that includes a declaration of honour that all presence detectors and daylight detectors are fine-tuned and checked.
- measurement of illumination with a lux meter [lx] that the minimum target illumination values are exceeded with at least 1 measurement per 15 m² of floor area, report with results.
- check the floor and wall coefficient of reflection [%] with a luminance and illuminance meter is in-line with assumptions. Check for impact of furniture. If the interior is much darker than assumed in the design file, issue a warning to the building owner. At least 10 surfaces should be checked per 100 m².
- measurement of the maximum luminaire power (PI [W/m²] and verify against the design value. If these deviate by more than 5% the design file needs to be updated.
- measurement of the maximum luminaire power (PI [W/m²] and verify against the design value. If these deviate by more than 5% the design file needs to be updated.

For other lighting applications the following data could be required:

- a checklist for BACS lighting functions that includes a declaration of honour that all presence detectors and daylight detectors are fine-tuned and checked.
- measurement of the maximum luminaire power (PI [W/m²] and verify against the design value. If these deviate by more than 5% the design file needs to be updated.
- measurement of the maximum luminaire power (PI [W/m²] and verify against the design value. If these deviate by more than 5% the design file needs to be updated.

A1.5.3 Control and adjustment requirements

Control and adjustment requirements could be set:

In addition to the previous requirements for control systems at the time of installation or renovation the following could be required for control systems:

- A requirement that lighting installations in common circulation areas in existing buildings should have a presence detector that controls lighting for useful floor areas of at least 50 m^2 and in staircases at least one per every three floor levels
- A requirement for non-residential buildings to have a central lighting management system and/or an automatic controller:
- that allows for unoccupied periods:
  - dimming to the minimum required levels if technically justified

or

- switching off lighting.
- for high occupancy rooms with available daylight, to have:
  - daylight dependent dimming
  - a controller loop every 25 m^2.

A1.5.4 Metering and monitoring requirements for continuous commissioning and adjustment

Although this was not found in the examples cited in Section 5, it is additionally proposed to require for large buildings (>1000 m^2) that there should be an energy monitoring system (EMS) or BACS function in place for lighting that measures:

- LENI [kWh/m^2/month]
- quarterly power data at least per area of (>200 m^2) and hereby:
  - detect the minimum consumption is the self-consumption (minimum power is the parasitic power)
  - to verify daylighting control functioning, a yearly check if the maximum power measured during June at 17 h (check all days of a month and keep the quarterly maximum value) >0.8 that of December
  - calculate seasonal (winter–spring–summer–autumn) aggregated statistics per day of week (Mon-Fri, Sat, Sun) computer equivalent operating hours equal to LENI/PI [h]
  - monitor the occupancy with at least one alternative parameter (e.g. lift operation, occupancy detectors, ICT up-time, etc.) and display data next to equivalent operating hours obtained from LENI/PI
  - to verify yearly occupancy control functions when anomalies are detected in the equivalent operating hours by considering the data collected.

If the measured LENI and PDI are not within the limits of the overall system energy performance requirements for two consecutive years than a relighting and redesign should be considered (i.e. new luminaires, controls and lighting design).

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