

Optimal energy management of urban rail systems: Key performance indicators



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ABSTRACT

Urban rail systems are facing increasing pressure to minimise their energy consumption and thusly reduce their operational costs and environmental impact. However, given the complexity of such systems, this can only be effectively achieved through a holistic approach which considers the numerous interdependences between subsystems (i.e. vehicles, operations and infrastructure). Such an approach requires a comprehensive set of energy consumption-related Key Performance Indicators (KEPIs) that enable: a multilevel analysis of the actual energy performance of the system; an assessment of potential energy saving strategies; and the monitoring of the results of implemented measures. This paper proposes an original, complete list of KEPIs developed through a scientific approach validated by different stakeholders. It consists of a hierarchical list of 22 indicators divided into two levels: 10 key performance indicators, to ascertain the performance of the whole system and complete subsystems; and 12 performance indicators, to evaluate the performance of single units within subsystems, for example, a single rail vehicle or station. Additionally, the paper gives a brief insight into urban rail energy usage by providing an adequate context in which to understand the proposed KEPIs, together with a methodology describing their application when optimising the energy consumption of urban rail systems.

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1. Introduction

Urban transportation is responsible for one fourth of the total CO₂ emissions produced by the transport sector in the European Union (EU) [7], which accounts for approximately 7% of the total greenhouse gas (GHG) emissions in the EU [15]. Furthermore, the dominance of the private car in urban areas results in high levels of congestion, noise and air pollution; a major constraint on the quality of life in many cities around the world [33]. Developing and promoting the use of integrated, accessible and environmentally friendly public transport systems is therefore vital to address the increasing levels of urbanisation, whilst reducing GHG emissions and enhancing living conditions in urban areas.

Urban rail is well placed to be at the core of such sustainable public transport networks given its high capacity, safety, reliability and absence of local emissions [34]. In addition, it typically generates proportionally lower GHG emissions than competing transport modes, although this depends on passenger load factors and the electricity generation mix [3]. Nevertheless, in the context of growing capacity demands and rising energy costs, where rival

modes are significantly improving their environmental performance, it is necessary that urban rail reduces its energy consumption while enhancing its service quality [19].

Energy consumption in urban rail systems is defined by a wide range of interdependent factors embracing vehicles, infrastructure and operations. Therefore, a broad understanding of the energy flows within the system is fundamental to develop successful energy efficiency programmes. Additionally, optimising the energy use in urban rail systems requires a structured, rational methodology that assists operators and designers in the appraisal of multiple energy saving solutions. Such a methodology needs to exhibit a comprehensive set of energy consumption-related Key Performance Indicators (KEPIs) at its core, as illustrated by Fig. 1. Hence, it should include a series of quantifiable parameters that allow a full understanding of the system's actual energy consumption, thusly facilitating in the identification of areas with a high energy saving potential. Additionally, if further related to business indicators, KEPIs will produce meaningful information for decision makers to select the optimal option amongst different energy efficiency strategies, e.g. by enabling benefit-cost assessments. Furthermore, they will be useful to monitor and evaluate the implemented energy efficiency measures.

Nevertheless, the complexity of urban rail systems – with a large amount of interrelated energy consumption factors that can

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Nomenclature

<i>A</i>	net floor area (m ²)
<i>AC</i>	alternating current
<i>ATO</i>	automatic train operation
<i>CCP</i>	common coupling point
<i>d</i>	distance travelled by trains (km)
<i>DAS</i>	driver advisory system
<i>DC</i>	direct current
<i>E</i>	energy consumption over a defined period of time (kWh)
<i>ESS</i>	energy storage system
<i>EU</i>	European Union
<i>f_(CO₂)</i>	conversion factor (kg CO _{2e} /kWh)
<i>GHG</i>	greenhouse gases
<i>HVAC</i>	heating, ventilation and air conditioning systems
<i>KEPI</i>	key energy performance indicator: the collective term for both KPIs and Pls
<i>KPI</i>	Key Performance Indicator
<i>L</i>	network length (km)
<i>LED</i>	light emitting diodes
<i>NP</i>	number of passengers
<i>PC</i>	passenger capacity
<i>PI</i>	Performance Indicator
<i>PMSM</i>	permanent magnet synchronous motor

Subscripts

<i>aux</i>	on-board auxiliary systems
<i>dep</i>	depot buildings
<i>el</i>	electrical energy
<i>HVAC</i>	heating, ventilation and air conditioning systems
<i>in</i>	inflow
<i>light</i>	lighting and information systems
<i>max</i>	maximum potential
<i>net</i>	net energy consumption (inflow minus outflow)
<i>non-trac</i>	for non-traction purposes
<i>out</i>	outflow
<i>park</i>	parked vehicle
<i>PF</i>	passenger flow-related system
<i>rec</i>	recovered energy
<i>ren</i>	energy produced from renewable sources
<i>st</i>	station
<i>sub</i>	substation
<i>sys</i>	whole system
<i>th</i>	thermal energy
<i>tun</i>	tunnel ventilation equipment/tunnel section
<i>veh</i>	vehicle in service

be potentially measured – makes the selection of suitable KEPIs a challenging and critical exercise. Currently, there is no consensus on how to assess the energy performance of urban rail systems among different stakeholders. Furthermore, this is a topic that has been traditionally overlooked in the academic literature.

To the best knowledge of the authors, the only rigorous attempt to identify energy performance indicators in railway systems has been developed within the *RailEnergy* project [25,24]. This approach consisted of seven indicators measuring the overall energy consumption of the system, the energy consumption share for parked trains, the rate of recuperated energy and the efficiency of the railway distribution grid. However, since this approach was developed to describe the global energy performance of railway systems (for both electric and diesel traction and passenger and freight transport) without providing information on the performance of different subsystems, it may not be considered as holistic. In fact, its authors admit that the proposed Key Performance Indicators (KPIs) cannot stand alone, but should be combined with a more in-depth analysis of the energy consumption at different system levels to avoid misleading results.

Hence, a multi-level aggregation of indicators appears to be the most suitable approach to define and evaluate energy efficiency measures in such complex systems as urban rail networks. This is a type of approach that has proved successful in assessing the energy performance of other complex systems, such as buildings [35], district heating networks [21] or industrial processes [28].

Therefore, this investigation utilises a holistic approach in order to develop a comprehensive set of indicators for assessing and optimising the energy consumption in urban rail systems; that is, a set of KEPIs facilitating the process described in Fig. 1. Thus, the paper starts by giving a brief insight into urban rail energy usage, to establish a clear context for the identification and definition of adequate KEPIs. A list of representative and measurable indicators is then defined together with its development process. This is complemented by a methodology that illustrates how to use the suggested KEPIs in the assessment of different energy efficiency measures. The final aim of this paper is to provide the basis for a complete decision-support tool to optimise the energy use in urban rail systems.

2. Overview of energy consumption in urban rail systems

2.1. General description of urban rail systems

“Urban rail” refers to different railway systems providing public transport services within metropolitan areas. This typically includes tramways, light rail systems, rail rapid systems (more generally known as metro) and regional or commuter railways [34].

Although different urban rail systems offer diverse features, particularly in terms of capacity and level of service, they all have a number of basic characteristics in common. Thus, the distance between stations is relatively short, ranging from 250–500 m in tramways to 1–5 km in commuter rail. Furthermore, all urban rail systems are electrically powered, with the exception of some regional services using diesel traction which are out of the scope of this work. As a result, urban rail systems present high operation performances, low levels of noise and no local air pollution. Other distinguishing features of urban rail include its high capacity, frequency, degree of safety and punctuality, the possibility of automation and low surface space needs. However, they typically require greater investment than non-rail transport modes.

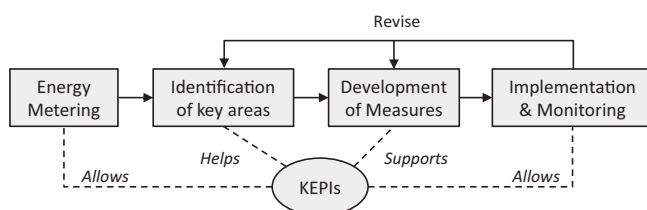


Fig. 1. Simplified methodology to measure and optimise the energy use of urban rail systems.

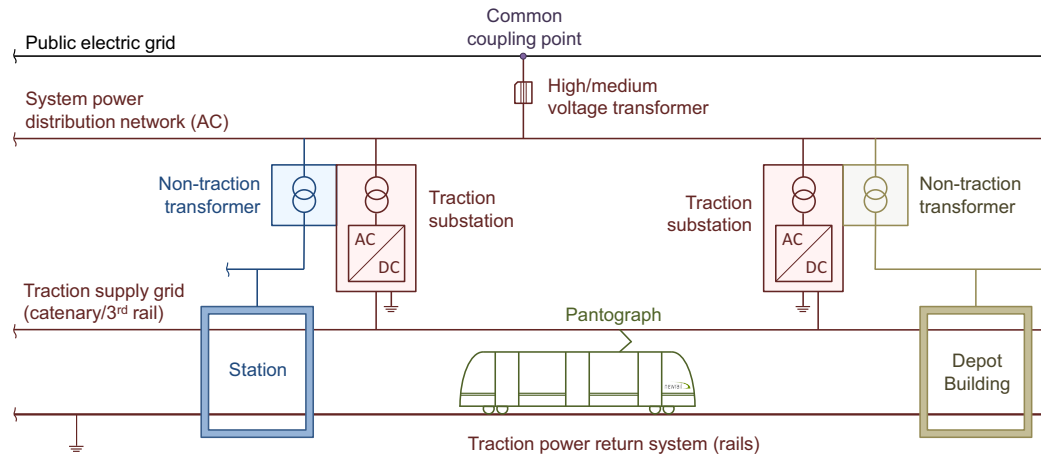


Fig. 2. Diagram of a typical power supply network in urban rail systems.

2.2. Urban rail energy use

Energy use in urban rail systems is typically classified into traction and non-traction consumptions. The former refers to the energy required to operate the rolling stock throughout the system, and includes propulsion and on-board auxiliary systems. The latter considers the energy consumed at stations, depots and other subsystems, e.g. signalling, tunnel lighting and ventilation, groundwater pumps, etc.

Fig. 2 shows a schematic representation of how the electrical energy is typically distributed in urban rail systems. The connexion point of the systems with the public grid is usually referred as common coupling point (CCP); a step-down transformer being the first element in the power distribution network of the system itself.¹ In order to condition the electric power from this grid to the rolling stock feeding requirements, a number of substations are located along the track. As most urban rail systems use direct current (DC) to power the rolling stock, generally at 600/750 V, 1500 V or 3000 V, they comprise of step-down transformers and rectifiers. These substations feed the traction supply grid, which typically consists of an overhead line (catenary) or a conductor rail (third rail). The rolling stock then collects this energy by means of pantographs in overhead power lines, and current collector shoes in third-rail systems. The electric power typically returns to the traction substations through the running rails or, less frequently, through an extra conductor rail (fourth rail).

Non-traction loads are generally supplied through specific transformers conditioning the power from the distribution network as required. Such transformers are independent of traction substations; but are often located together, as illustrated for the case of the stations and depot buildings in Fig. 2.

2.2.1. Traction energy consumptions

Fig. 3 shows a characteristic traction energy flow chart for urban rail systems; the result of an amalgamation of different sources available in the literature. This includes estimations for energy consumption breakdown in generic metro systems [26] and regional railways [12], results from research projects on urban rail energy efficiency such as *ElecRail* [9] and *ModUrban* [13], as well as energy data from particular systems such as Blackpool tramway [5], Bilbao metro, [20], Brussels metro [2], Oslo metro [27] and London Underground [4]. Therefore, Fig. 3 should only be taken as an illustrative example of the typical

energy distribution in urban rail, as this may differ significantly between individual systems. Following the colour pattern introduced in Fig. 2, this diagram represents the energy flows across the traction power supply system in red shades, whilst the energy distribution within the rolling stock is shown in green shades.

Energy losses in the power supply system (i.e. from the CCP to the pantograph/collector shoes) will fundamentally depend on the supply voltage and traffic load [29]. These can range from 22% in 600V-DC networks to 6% in 3000V-DC systems [22].

Regarding the energy flows within the rolling stock itself, Fig. 3 reveals that approximately half of the energy entering the rolling stock is dissipated during braking. However, this proportion will depend principally on the frequency of stops, being greater for tramways and metros than for regional services. Given the capability of electric motors to act also as generators, it is possible to recover a substantial part of the braking energy [10]. This regenerated energy may be stored in onboard energy storage systems (e.g. batteries and supercapacitors) and used to drive on-board auxiliary systems, or can be returned to the power supply grid for use by other vehicles [30]. Nevertheless, approximately one third of braking energy is irreversibly dissipated, due principally to losses in motors, converters and the transmission system.

Another important area where losses occur is in the traction process itself. Thus, the following energy efficiencies have been reported [9]: between 98.5% and 99.5% for converters; 90–94% for DC and induction motors, the most commonly used in urban rail; 96–98% for the transmission system.

On-board auxiliary systems typically represent a major share of the traction energy consumption. Auxiliary systems consist of the equipment that maintains good on-board conditions, both in terms of vehicle's operational capacity (traction cooling systems, compressors, etc.) and the passengers' comfort functions (i.e. heating, ventilation and air-conditioning (HVAC), lighting and information systems). HVAC equipment is generally responsible for the greatest proportion of this consumption, although this varies notably depending on the climatic conditions in which the individual system operates [1].

The remaining energy entering the rolling stock is dedicated to overcoming its motion resistance, including both mechanical and aerodynamic resistances. Given the relatively low velocities of urban rail services, the greatest part of the resistance is generally caused by the mechanical friction between the rails and wheels, with the rolling stock mass having an important influence on the overall impact.

¹ It should be noted that in certain systems substations draw power directly from the public grid, without the need of the AC power distribution network.

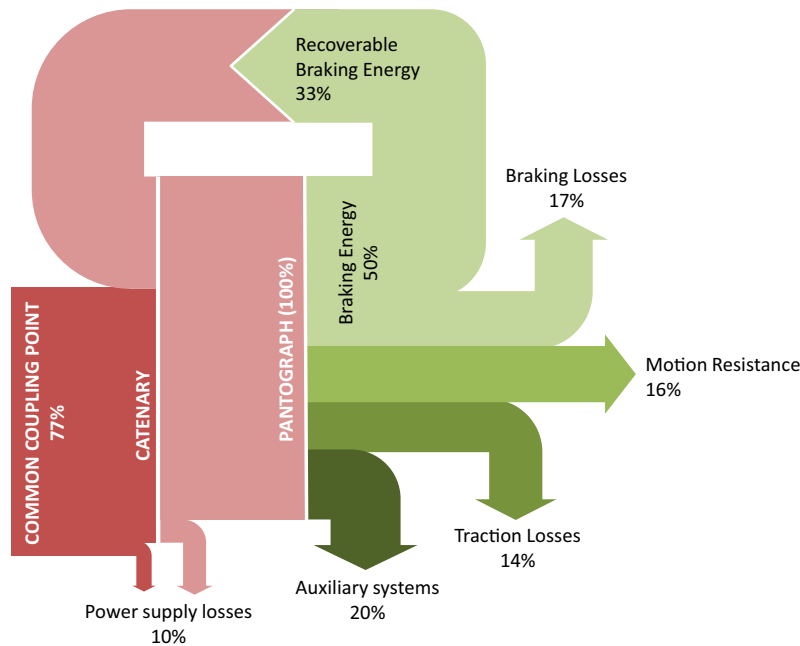


Fig. 3. Illustrative traction energy flow diagram for urban rail systems.

2.2.2. Non-traction energy consumptions

Non-traction energy consumption covers the energy utilised in passenger stations, depots and other infrastructure-related facilities, such as tunnel ventilation systems, groundwater pumps, tunnel lighting, signalling and the cooling equipment in technical rooms. The majority of the aforementioned systems are electricity-powered, although some thermal systems exist in stations and depots, typically gas-fired boilers to provide heating and hot water [8].

The principal energy-demanding systems in stations typically include lighting, HVAC, escalators, lifts and information screens. In underground stations, the HVAC equipment is usually responsible for the greatest proportion of energy consumption, as temperatures may reach very high levels due to train operations [16,14]. Therefore, tunnel ventilation systems play a vital role in improving the thermal comfort in subway stations, but also in the rolling stock itself [31].

The energy consumption in depots is principally related to the inspection, maintenance and cleaning of vehicles [32]. Apart from the energy required to run the depot facilities themselves, this includes the energy consumed by the on-board auxiliary systems that must remain on while vehicles are parked, either to facilitate the aforementioned operations or during stabling periods [23].

The proportion of the non-traction energy consumption is strongly influenced by the type of system and climate conditions. Thus, it will be considerably smaller in tramways than in underground metros, where it represents roughly one third of the total energy consumption on average [8].

3. Methodology to develop Key Energy Performance Indicators (KEPIs) for urban rail systems

This section presents the initial requirements and the methodology of the investigation carried out to develop a complete set of KEPIs that helps optimising the energy use in urban rail systems.

3.1. Initial requirements

The complexity of urban rail systems may require a large number of indicators covering different aspects of the system energy con-

sumption. Therefore, the selected indicators should extract solely the most relevant information about the system energy performance in order to limit their number. However, they must also provide an accurate, global picture of the current energy performance, which is essential to help identify effective energy saving measures. Furthermore, the selected set of KEPIs should facilitate the definition of future performance targets while providing a mechanism to monitor the progress of implemented energy efficiency measures. More specifically, they should meet the following requirements:

- Valid for all types of urban rail system; i.e. tramways, metros, etc.
- Inclusive and holistic: They should provide energy consumption information at different levels (e.g. total network, total vehicles, one vehicle's auxiliaries, one station, etc.). Additionally, they should capture the interdependences between subsystems.
- Wide-ranging: they should cover specific issues such as energy efficiency, energy recovery, thermal energy management, renewable energy usage and CO₂ emissions.
- Hierarchical: their organisation should indicate their relative importance in the system performance.
- Quantifiable, clearly defined and scientifically valid.
- Sufficiently simple and easy to interpret for different stakeholders.
- Descriptive: they should facilitate evaluation and comparison between different energy efficiency strategies.
- Inspiring: they do not have to be all measurable within a particular system, but they might stimulate further metering advances in such system.
- Suitable for decision making support in both existing and new systems.
- Representative: they should provide a basis for comparison between different systems.
- Flexible: they should be open to further improvement.

3.2. Research methodology

The list of KEPIs presented in this paper has been developed following a consensus oriented process that involved all relevant

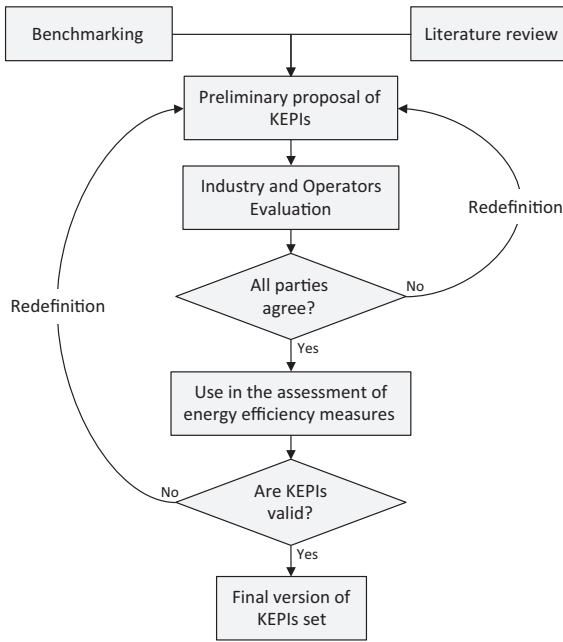


Fig. 4. Methodology diagram to elaborate a holistic set of KEPIs for urban rail systems.

stakeholders. As illustrated in Fig. 4, the process started by undertaking an extensive review of the literature on railway energy consumption, including academic papers and former/running state-of-the-art projects. This led to a preliminary set of indicators developed by the authors, subsequently revised and updated

through constructive discussions including representative partners from industry, operators and public transport authorities. A complete set of KEPIs were agreed amongst all stakeholders and finally validated through their use in the assessment of different energy saving measures.

It should be noted that the methodology presented herein will remain valid for further development or improvement of the set of KEPIs by different stakeholders.

4. Results: Holistic set of KEPIs for urban rail systems

With the aim of providing a holistic and hierarchical assessment of the energy performance in urban rail systems, two different levels of indicators have been introduced: key performance indicators and performance indicators, which together form the energy consumption-related Key Performance Indicators (KEPIs). These are described further in turn below:

- **Key Performance Indicators (KPI):** to evaluate the performance of the whole system and complete subsystems (e.g. fleet of trains, all the stations in the system, etc.). They will enable the ascertaining of fundamental parameters, such as the system-specific energy usage (and corresponding CO₂ emissions) or the weight of different subsystems in the global energy consumption. They will also reflect how different improvements at subsystem level affect the global system performance.
- **Performance Indicators (PI):** to analyse the performance of single units within subsystems, for example a single rail vehicle or station. They may be used in the evaluation of individual energy efficiency measures at subsystem level, whilst providing essential information to calculate different KPIs at global scale.

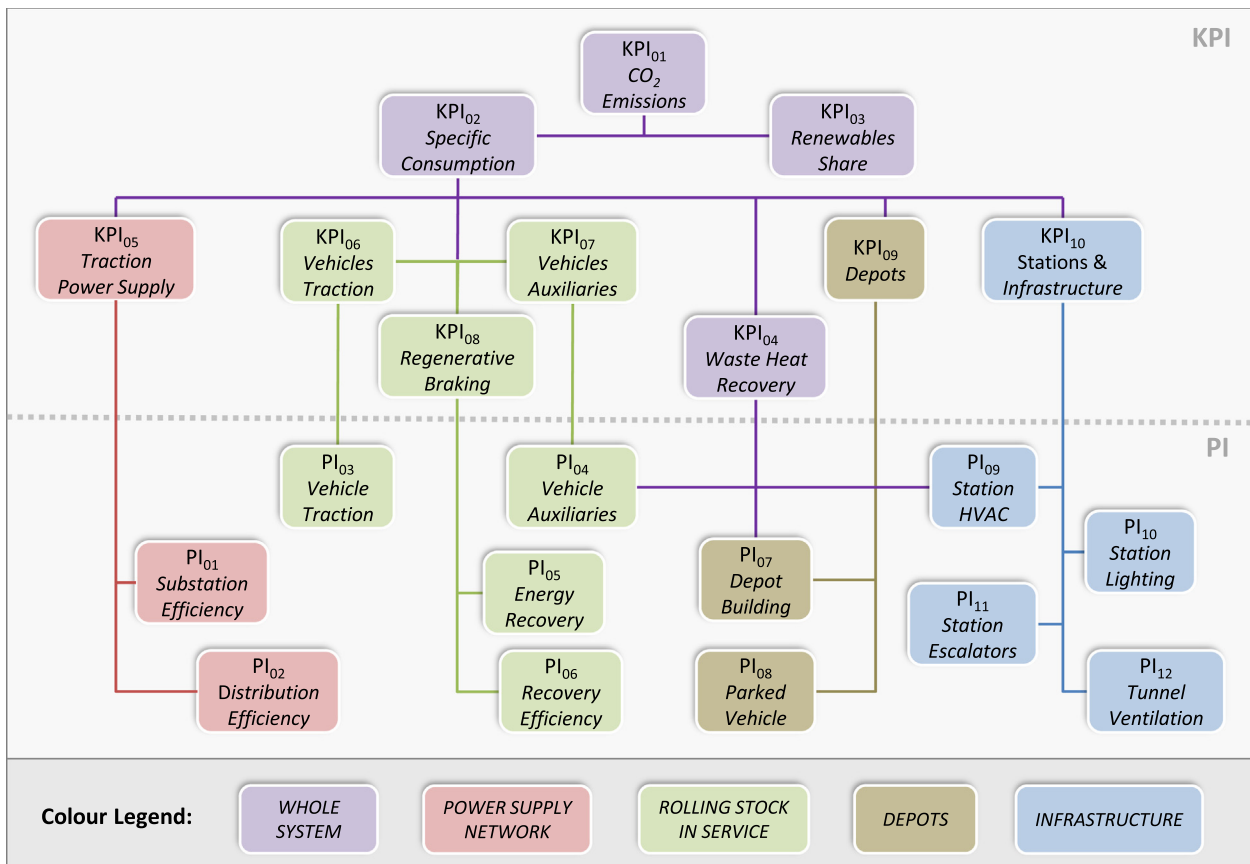


Fig. 5. Structure of the proposed set of KEPIs.

Fig. 5 shows the complete set of KEPIs developed as a result of this investigation. It consists of a list of 10 KEPIs and 12 PIs which covers the energy performance of the whole system and its main subsystems, namely the power supply network, rolling stock, depots and infrastructure. It should be noted that Fig. 5 groups the indicators referring to the same subsystem by colours, the colour coding being consistent with Figs. 2 and 3. Additionally, this diagram represents the link between KEPIs and PIs, which will be discussed in further detail later in the paper.

4.1. List of Key Performance Indicators (KEPIs)

4.1.1. KPI_{01} – Specific CO₂ emissions

This indicator reflects the yearly amount of CO₂ equivalent emissions (CO₂e) associated with the energy consumption of the whole system per unit of transportation. It is measured in kg CO₂e per passenger-km and can be used to compare the environmental impact of different urban rail systems between themselves or against other transport modes. Its calculation requires knowing the total energy consumption by type of source in the system $E_{(sys)(i)}$ (e.g. electricity, gas, renewable energies, etc.) and their respective CO₂ conversion factors $f_{(CO_2)(i)}$, which in the case of the UK can be obtained from the UK Government [6]. It can be assessed by using Eq. (1), where $NP_{(sys)}$ represents the total number of passengers using the system yearly and $d_{(sys)}$ stands for the total distance travelled by all trains in the system yearly.

$$KPI_{01} = \frac{\sum_i E_{(i)(sys)} \cdot f_{(CO_2)(i)}}{NP_{(sys)} \cdot d_{(sys)}} \quad (1)$$

4.1.2. KPI_{02} – Specific energy consumption

This indicator measures the global efficiency of the system by providing information on its total yearly energy consumption per passenger-km, which includes both electrical and thermal energy, i.e. $E_{(el)(sys)}$ and $E_{(th)(sys)}$, respectively (Eq. (2)). It should be noted that $E_{(el)(sys)}$ comprises not only the electricity drawn from the public network through the CCP, but also all electricity generated within the proper system, either from renewable or from fossil sources. The energy drawn from the public network must be calculated as inflow minus outflow power at the CCP; that is, the part of the regenerated braking energy that is sent back to the public grid must be accounted as outflow. This KPI is typically used to establish general performance comparisons between different transport modes. However, its capacity to compare different urban rail systems is limited as they present unique characteristics that affect their performance. Furthermore, this is not the most adequate indicator to assess the effect of particular energy saving measures as it depends on the degree of occupancy, hence the necessity to define more specific KPIs.

$$KPI_{02} = \frac{E_{(el)(sys)} + E_{(th)(sys)}}{NP_{(sys)} \cdot d_{(sys)}} \quad (2)$$

4.1.3. KPI_{03} – Share of renewable energy

This indicator refers to the percentage of the system's yearly energy consumption that is supplied by renewable energy sources generated within the system itself. Having a direct influence on KPI_{01} , it can be seen as a measure of the effort made by the system to reduce its environmental impact, which, if successful, could be used to strengthen its public image. Both electricity and thermal energy coming from renewable sources ($E_{(el)(sys)(ren)}$ and $E_{(th)(sys)(ren)}$ respectively) must be taken into account, as indicated by Eq. (3).

$$KPI_{03} = \frac{E_{(el)(sys)(ren)} + E_{(th)(sys)(ren)}}{E_{(el)(sys)} + E_{(th)(sys)}} \times 100 \quad (3)$$

4.1.4. KPI_{04} – Waste heat recovery

All energy consumed within a system is eventually transformed into waste heat; the recovery of which could help reduce the total energy consumption in the system. Aiming to quantify the energy savings produced by such measures, KPI_{04} is defined as the percentage of the total energy usage that is recovered and reused as waste heat within the system (Eq. (4)). As illustrated by Fig. 5, waste heat can be typically recovered at vehicle level for heating purposes, e.g. from braking resistors or other traction equipment; at infrastructure level, e.g. for heating underground stations and staff rooms, either by directly using warm air in tunnels or through heat pumps; and in depots, e.g. by using cogeneration systems.

$$KPI_{04} = \frac{E_{(th)(sys)(rec)}}{E_{(el)(sys)} + E_{(th)(sys)}} \times 100 \quad (4)$$

4.1.5. KPI_{05} – Traction power supply efficiency

This indicator evaluates the efficiency of the traction power supply system, which includes both the substations and the power distribution network. In other words, it accounts for the energy losses between the CCP and the connection point of the traction power supply grid to the rolling stock (pantograph or collector shoes). It is defined as the yearly net² electricity consumption of all trains in the system while they are in service $E_{(el)(sys)(veh)(net)}$ over the total energy consumption for traction purposes measured at substation level, as shown by Eq. (5).

$$KPI_{05} = \frac{E_{(el)(sys)(veh)(net)}}{E_{(el)(sys)} - E_{(el)(sys)(non-trac)}} \times 100 \quad (5)$$

4.1.6. KPI_{06} – In-service traction energy consumption

This KPI assesses the amount of energy specifically used for traction purposes in the system per year and unit of transportation, excluding the consumption of on-board auxiliary systems $E_{(el)(sys)(veh)(aux)}$, (Eq. (6)). It is intended to reflect the energy savings generated at system level by different energy measures applied to the vehicle's traction system. Additionally, it can be useful to compare the fleet energy performance of different systems, although the influence of such parameters as the track profile or the stops frequency should be considered.

$$KPI_{06} = \frac{E_{(el)(sys)(veh)(net)} - E_{(el)(sys)(veh)(aux)}}{NP_{(sys)} \cdot d_{(sys)}} \quad (6)$$

4.1.7. KPI_{07} – In-service auxiliaries' energy consumption

This KPI expresses the annual energy consumption of all vehicles' auxiliaries in the system per passenger-km, as given by Eq. (7). It can be useful to evaluate different energy efficiency measures focussed on, for example, lighting or comfort functions. However, this information should be considered carefully as climatic conditions may have a considerable influence on such consumption. For the same reason, the capacity of this indicator to compare different rail systems is limited.

$$KPI_{07} = \frac{E_{(el)(sys)(veh)(aux)}}{NP_{(sys)} \cdot d_{(sys)}} \quad (7)$$

4.1.8. KPI_{08} – Braking energy recovery

This indicator is intended to quantify the energy savings achieved in the whole system through the use of regenerative

² It is defined as the electrical energy flow entering the vehicle minus the part of the regenerated braking energy that is returned back to the power supply system.

Table 1
List of Performance Indicators (PIs).

Performance indicator	Definition	Equation
PI ₀₁ – Electrical substation efficiency	Total energy flow at the exit of a particular substation over the total energy flow at its entrance for a given load cycle	$PI_{01} = \frac{E_{(el)(sub)(out)}}{E_{(el)(sub)(in)}} \times 100$
PI ₀₂ – Power distribution line (catenary) efficiency	Total energy flow at the entrance of the rolling stock over the total energy flow at the exit of the substation for a given section of line under a predefined load cycle	$PI_{02} = \frac{E_{(el)(veh)(net)}}{E_{(el)(sub)(out)}} \times 100$
PI ₀₃ – In-service traction energy consumption	Traction energy consumption of a single vehicle per passenger-km for a given duty cycle	$PI_{03} = \frac{E_{(el)(veh)(net)} - E_{(el)(veh)(aux)}}{NP_{(veh)} \cdot d_{(veh)}}$
PI ₀₄ – In-service auxiliaries' energy consumption	Auxiliaries' energy consumption of a single vehicle per passenger-km for a predefined duty cycle	$PI_{04} = \frac{E_{(el)(veh)(aux)}}{NP_{(veh)} \cdot d_{(veh)}}$
PI ₀₅ – Braking energy recovery	Percentage of a single vehicle's gross traction power consumption (measured at pantograph level) that is regenerated during braking for a given duty cycle	$PI_{05} = \frac{E_{(el)(veh)(rec)}}{E_{(el)(veh)(in)}} \times 100$
PI ₀₆ – Braking energy recovery efficiency	Percentage of the maximum potential for regenerative braking energy recovery that is actually regenerated in a single vehicle during a given duty cycle	$PI_{06} = \frac{E_{(el)(veh)(rec)}}{E_{(el)(veh)(rec)(max)}} \times 100$
PI ₀₇ – Depot building's energy consumption	Energy use in a single depot building per unit of net floor area for a predefined operational cycle	$PI_{07} = \frac{E_{(el)(dep)} + E_{(th)(dep)}}{A_{(dep)}}$
PI ₀₈ – Parked vehicle's energy consumption	Energy consumption of a single parked vehicle per passenger capacity unit for a given duty cycle	$PI_{08} = \frac{E_{(el)(park)}}{PC_{(veh)}}$
PI ₀₉ – Station HVAC energy consumption	Energy consumed by HVAC systems in a single station per square meter, given a predefined operational cycle	$PI_{09} = \frac{E_{(el)(st)(HVAC)} + E_{(th)(st)(HVAC)}}{A_{(st)}}$
PI ₁₀ – Station lighting & information systems energy use	Energy used for lighting and information purposes within an individual station per square meter under a predefined operational cycle	$PI_{10} = \frac{E_{(el)(st)(light)}}{A_{(st)}}$
PI ₁₁ – Station passenger flow-related energy use	Specific energy consumption of a single passenger flow-related system for a given operational regime; this comprises lifts, escalators and other passenger conveyor systems	$PI_{11} = \frac{E_{(el)(st)(PF)}}{NP_{(st)(PF)}}$
PI ₁₂ – Tunnel ventilation energy consumption	Energy used by ventilation systems in a specific underground section per m ³ of tunnel volume under predefined operational conditions	$PI_{12} = \frac{E_{(el)(tun)}}{V_{(tun)}}$

braking technologies. It is defined as the percentage of the yearly gross³ traction energy consumption that is recovered during braking of all trains in the system (Eq. (8)); this includes both the electricity sent back to the traction power supply grid and the energy reused and stored within the vehicles themselves. It enables the evaluation and comparison of different strategies and technologies to increase the use of regenerative braking within the same system. However, it could be misleading if different rail systems are to be compared, since the capacity to recover the braking energy is greatly influenced by the track profile, timetables and other characteristics that are inherent to each particular system.

$$KPI_{08} = \frac{E_{(el)(sys)(veh)(rec)}}{E_{(el)(sys)(veh)(in)}} \times 100 \quad (8)$$

4.1.9. KPI₀₉ – Energy consumption in depots

This indicator computes the total energy consumption in depots, comprising the energy used by parked trains $E_{(el)(sys)(park)}$ and the thermal and electrical energy consumption of depot buildings ($E_{(el)(sys)(dep)}$ and $E_{(th)(sys)(dep)}$ respectively), as expressed by Eq. (9). In order to enable the assessment of different energy efficiency measures, this KPI includes the passenger capacity of all the trains in the system in its denominator $PC_{(sys)}$, as this is considered an easy-to-obtain parameter that is directly related to the energy consumption in depots. If used to compare depots' performance between different systems, climate conditions should be taken into account as they may affect the consumption of both vehicles and buildings.

$$KPI_{09} = \frac{E_{(el)(sys)(park)} + E_{(el)(sys)(dep)} + E_{(th)(sys)(dep)}}{PC_{(sys)}} \quad (9)$$

4.1.10. KPI₁₀ – Energy consumption in stations and infrastructure-related equipment

This indicator expresses the energy consumption of all station- and infrastructure-related equipment in the system per km of net-

work. The infrastructure-related equipment typically comprises tunnel ventilation systems as a major energy consumer, shown as $E_{(el)(sys)(tun)}$ in Eq. (10). However, other equipment could be included in this KPI depending on the particular case. Regarding the energy use in stations, it should be noted that this comprises both thermal and electrical energy consumptions ($E_{(th)(sys)(st)}$ and $E_{(el)(sys)(st)}$ respectively). This KPI may be used to evaluate and compare different energy saving measures within the same system, but it is not adequate to compare different systems as their infrastructure characteristics are generally unique.

$$KPI_{10} = \frac{E_{(el)(sys)(st)} + E_{(th)(sys)(st)} + E_{(el)(sys)(tun)}}{L_{(sys)}} \quad (10)$$

4.2. List of Performance Indicators (PIs)

PIs are intended to ascertain the effect of multiple energy saving measures on specific parts of the system, which can be done either by testing the proper technology/strategy on site or via simulations. Thus, they will provide fundamental information to aid the decision on whether a certain measure should be implemented throughout the entire system or not. It should be noted that the definition of duty cycles and operational regimes is indispensable for these PIs to provide valid comparisons of measures; although this lies outside the scope of the present paper.

Table 1 lists the twelve PIs produced as a result of the present investigation, including their definitions and corresponding equations (see also Fig. 5). It should be noted that this is by no means a fixed list of PIs, but one that refers to most relevant consumptions at subsystem level in typical urban rail systems. In fact, depending on the particular characteristics of each system, new PIs could be added to assess the energy performance of facilities that contribute significantly to the energy breakdown of the system; e.g. the cooling equipment of railway technical rooms in hot climate conditions, the signalling system, the underground water pumps, etc. It is also interesting to note that this list of PIs may be used in the calculation of the previously defined KPIs. For instance, it would be possible to ascertain KPI₀₉ by knowing PI₀₇ and PI₀₈ for all depot buildings and parked vehicles in the system, respectively. More relationships between different PIs and KPIs can be extracted from Fig. 5.

³ It is the electrical energy drawn by vehicles from the power supply system without considering the part of the regenerated braking energy that is returned to the power supply system.

5. Discussion on the use of the proposed list of KEPIs to optimise urban rail energy consumption

5.1. Procedure to apply the proposed list of KEPIs

Fig. 6 illustrates the role of the proposed set of KEPIs in assessing and optimising the energy consumption of urban rail systems. Firstly, KPIs are useful to describe a complete picture of the actual energy usage in the system from on-site measurements (baseline). This information will subsequently allow the identification of the key areas for improvement, establishing target energy savings and preselecting a group of actions to achieve them. Such measures will generally have to be evaluated at unit level before their implementation at system level. That is, it will be necessary to assess, either experimentally or by simulations, their energy saving effect in a particular unit, under predefined conditions. The PIs in Table 1 are specifically developed for this purpose.

The effect of those measures delivering significant energy savings at unit level will be then obtained at system level. Given the difficulty and costs involved in testing measures at large scale, this process will normally need the use of simulation programmes. In certain cases such as lighting replacement in stations, the energy savings extrapolation from a single unit to the whole system is reasonably straightforward. However, such measures as introducing on-board regenerative braking technologies or applying eco-driving strategies will require more complex calculations that consider all possible interactions between different subsystems (e.g., increase in vehicle mass due to on-board energy storage systems, reduction in available braking energy due to energy efficient driving, etc.). Once the new energy consumption scenario is defined by recalculating the relevant KPIs, a comparison against the current situation will be made in order to determine whether the energy savings at system level are still significant (note that due to the aforementioned subsystem's interactions the energy saving effect of some measures could become negligible at system level). If so, a benefit-cost assessment of the measure in question will be required to decide on its ultimate implementation. Lastly, the proposed list of KPIs will be useful to monitor the real performance

of the applied measures, which may provide valuable information to readjust them and, therefore, obtain optimised outcomes.

While additional KPIs or PIs may need to be removed or added (depending on the nature of the system in question), the methodology described herein can nevertheless be used by urban rail systems throughout the world to successfully monitor, assess and benchmark their energy consumption characteristics.

5.2. Energy efficiency measures and KEPIs

The proposed set of KEPIs was structured in such a manner that KPI₀₁ and KPI₀₂ would respectively account for the CO₂ emissions reduction and energy savings produced at system level by any measure (see Fig. 5). However, ascertaining the effect of those measures on different subsystems is also crucial to develop optimal energy efficiency strategies. With the purpose of further clarifying and illustrating the use of KEPIs, Table 2 indicates which of the suggested KPIs and PIs would be most relevant for the evaluation of different energy measures typically available for urban rail. Further explanation on the listed measures can be found in Ref. [11], which provides an extensive and up-to-date overview on the matter.

Table 2 shows the main KPIs associated with each measure, but also other KPIs that would reflect the secondary effect of that particular measure on other subsystems. For example, all actions destined to minimise the traction losses in the power supply system and the rolling stock itself would ultimately mean a reduction of the thermal load in tunnels; hence reducing the energy demand of tunnel ventilation systems and both on-board and in-stations HVAC equipment (KPI₀₇ and KPI₁₀). Furthermore, the use of regenerative braking technologies, together with the application of eco-driving techniques and driver advisory systems (DAS), would shave the power peaks in the line [17,18]; therefore reducing the distribution energy losses (KPI₀₅). Lastly, it should be taken into account that improvements on the vehicle comfort functions could mean significant mass increase, thus increasing the traction energy consumption (KPI₀₆).

In addition to the measures listed in Table 2, there exist a group of actions that, rather than aiming to reduce the system energy

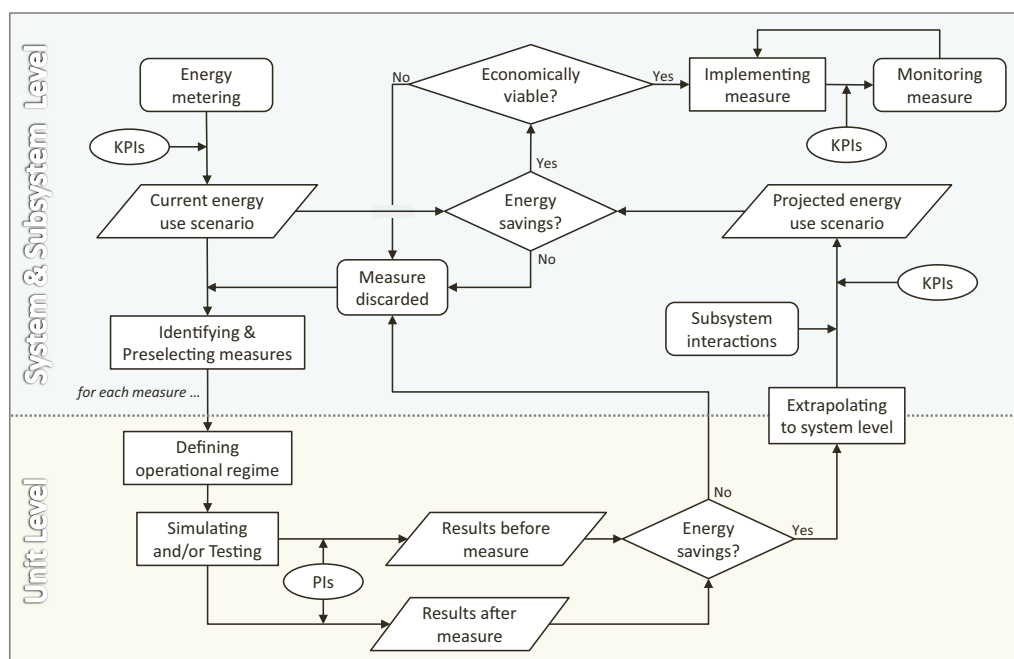


Fig. 6. Schematic representation of the use of KEPIs in the development of energy efficiency measures for urban rail systems.

Table 2

Summary of energy saving measures for urban rail systems and their relationship with the proposed set of KEPIs.

Energy efficiency measures		Main Pls	Main KPIs	Secondary KPIs
Subsystem affected	Solution			
Power supply	Efficient transformers	PI ₀₁	KPI ₀₅	KPI ₀₇ , KPI ₁₀
	Efficient rectifiers	PI ₀₁		
	Low resistance conductor	PI ₀₂		
Rolling stock	PMSMs	PI ₀₃	KPI ₀₆	KPI ₀₅ , KPI ₀₇ , KPI ₁₀
	Traction software optimisation	PI ₀₃		
	Lighter materials	PI ₀₃		
	Efficient converters	PI ₀₃		
	Stationary ESS	PI ₀₅ , PI ₀₆	KPI ₀₆ , KPI ₀₈	KPI ₀₅ , KPI ₀₇ , KPI ₁₀
	On-board ESS	PI ₀₃ , PI ₀₅ , PI ₀₆		
	Reversible substation	PI ₀₅ , PI ₀₆		
	Timetable optimisation	PI ₀₅ , PI ₀₆		
	Eco-driving techniques	PI ₀₃	KPI ₀₆	KPI ₀₅ , KPI ₀₇ , KPI ₁₀
	DAS	PI ₀₃		
	ATO	PI ₀₃		
	Improved body thermal insulation	PI ₀₄	KPI ₀₇	KPI ₀₆
	Efficient heat pumps for heating/cooling	PI ₀₄		
	LED lighting	PI ₀₄		
	Improved control of HVAC & lighting	PI ₀₄		
Depots	LED lighting	PI ₀₇	KPI ₀₉	–
	Geothermal heat pumps	PI ₀₇		
	Improved control of HVAC & Lighting in parked vehicles	PI ₀₈		
Infrastructure	Geothermal heat pumps	PI ₀₉	KPI ₁₀	–
	Improved control of HVAC in waiting areas	PI ₀₉		
	LED lighting	PI ₁₀		
	Improved control of lighting in waiting areas	PI ₁₀		
	Improved control of passenger conveyor systems	PI ₁₁		
	Low-energy tunnel cooling	PI ₁₂		

consumption themselves, seek to increase the system's energy self-sufficiency and also reduce its associated CO₂ emissions. This is the case for instance of the generation of renewable energy and the recovery of waste heat within the proper system, whose effect would not be directly reflected by KPI₀₂, but by KPI₀₁. The increase in the share of renewable energy would be covered by KPI₀₃, whereas the recovery of waste heat would be registered by KPI₀₄.

6. Conclusions

A holistic approach has been used to produce a comprehensive set of performance indicators for assessing and optimising the energy consumption in urban rail systems. It is believed that such an approach has not previously been developed, representing a methodology through which the energy performance of urban rail systems can be compared and contrasted. This process has included the essential active involvement of different stakeholders to guarantee a meaningful outcome. It consists of a hierarchical list of KEPIs that enables: (a) multilevel analysis of the current energy performance of the system; (b) assessing and comparing different energy efficiency strategies; (c) monitoring the progress of the implemented measures. This set of KEPIs and its associated methodology are the necessary basis of a complete decision-support tool to optimise the energy use in urban rail systems.

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