A Systemic Framework for Monitoring Energy Performance of Urban Railways

Roberto Palacín

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ABSTRACT

Global sustainability challenges are particularly acute in urban conurbations which house the majority of the world's population and where most of the economic activity takes place. Mobility is at the core of this challenge as transport is one of the highest energy consuming and polluting sectors across the globe. Achieving a low environmental impact transport system fit for all is a clear objective. A modal shift to low energy but highly competitive transport modes is a key target. Urban railway systems have the environmental performance and mass transit capability to be the core provider of mobility in metropolitan areas bringing also other benefits e.g. connectivity, cohesion and social inclusivity. Nevertheless, in a very competitive context where all modes are improving their energy performance, it is crucial that urban rail systems enhance their energy conservation levels without jeopardising their service offer.

There is a lack of consensus amongst stakeholders on how to assess energy performance of urban rail systems. This void has been extended to the academic literature, where the issue is largely missing. The overall purpose of this thesis is to contribute to energy conservation of urban rail systems by supporting the decision-making process leading to the deployment of interventions aimed at improving energy efficiency and optimising its usage. A three-phased methodological triangulation approach has been adopted to address three research questions derived from two research objectives.

This research has investigated energy usage, interventions and interdependencies that are governed by the complexity of the socio-technical system that are urban railways. A holistic approach has been developed based on an adaptable systemic monitoring framework and associated methodology enabling i) a multilevel analysis of system energy performance using a set of twenty-two hierarchical indicators and four complementing parameters, ii) an appraisal of candidate energy optimisation interventions and iii) the monitoring of the results of implemented measures. To validate and illustrate its execution, the framework has been applied to five different urban rail systems to assess a total of eleven technical and operational interventions. This has resulted in observing up 3.4% or circa 4 GWh usage reduction at system level when considering the influence of the three technical interventions monitored and up to 4.8% or circa 6.6 GWh when the eight operational interventions are evaluated in conjunction. These outcomes have illustrated the universality of the framework and its adaptability to the particularities of each urban rail system.

To Oliver and Anna, you can do it.

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I would like to extent my gratitude to Prof. Mark Robinson, my original supervisor, for giving me the opportunity to do this Doctorate and more importantly for his trust and support over the time we have known each other. Thank you for having faith in me all those years ago.

I am extremely grateful to Prof. John Mangan, who agreed to be my second supervisor when I needed it the most. I will be forever indebted to him for his kindness and generosity, which goes beyond and above the expected. I have learned so much from you and I only wish I will be able to continue to do so in the future.

None of the above would have mattered the slightest if it weren’t for my family.

CONTENTS

LIST OF FIGURES

LIST OF TABLES

Chapter 1 - INTRODUCTION

The purpose of this research is to understand how energy is used in urban railway systems, identify the critical consumption flows and determine how to monitor them. This is an essential step towards introducing interventions seeking the optimisation of the overall energy performance of the system, improving energy conservation rates and reduce the efficiency gap. In the context of this research, the term energy refers to electric power supply unless stated otherwise. This first chapter introduces the overall thesis rationale, which includes the background to the research, the research questions being addressed, the contribution to knowledge of the research presented in this thesis and its structure into eight chapters.

1.1. Background to the Research

The transport of people and goods is an essential driver of our society, economy and way of living. Similarly, there is increasing significance in adopting more sustainable and clean mobility solutions that would allow us to continue on our path of growth and prosperity. A low environmental impact transport system fit for all is a clear objective and challenge. This is particularly relevant in urban conurbations where the highest proportion of the population lives and where most economic activity takes place (Roskilly *et al.*, 2015).

In the vast majority of cases mobility is and will be provided by multiple transport mode options. Choice, therefore, is already a key factor defining the composition of the mobility chain. Environmental performance and mass transit capacity are but two of railway's characteristics that should position this mode at the core of a sustainable mobile society. Significant competition from other modes is strong, particularly in the automotive sector where innovation is driving a competitiveness stride that threatens to dominate the transport offer, although questions remain about the viability and sustainability of such dominance (e.g. congestion of the road network). Modal shift to a low energy but highly competitive transport mode is a key challenge faced by the railways.

The geography and urban planning research communities have long explored the relationship between transport, urban form, mobility and other socio-economic aspects. An interesting and relevant outcome of such discourse is the realisation of the displacement of the conventional clearly delimited model of a compact central city, suburban surrounds and defined rural periphery. This established model has been substituted by a more complex polycentric pattern of urban concentration devolved around multimodal (and multi-technology) public transport networks with radial and orbital links (Hickman *et al.*, 2013). Both models favour the use of rail systems as core vertebrae of these cities. Examples of the former include the 1950s

Stockholm General Plan around the *Tunnelbana*, the 1960s Paris *Schéma Directeur* using the *Résau Express Régional* (RER) and the German *S-Bahn* networks, which extended the quality of urban rail networks deep into rural parts surrounding cities. London is a good case of a polycentric structure with railway developments such as Thameslink, Crossrail and the future Crossrail 2 being the core agents for the creation of a city-region (Hall, 2009; 2013; Hickman *et al.*, 2013). Sir Peter Hall (2009) argued that when forecasting the future of the city-region in the 21st century, railways promise to do what the motorways failed to achieve in the 20th century: Shrinking geographical space to create single polycentric megapolis.

This context of global urbanisation is highly relevant to the contemporary sustainability agenda and meeting the challenges derived from the climate change process. Central to efforts to curb the effects of this phenomenon is the Kyoto Protocol, which set global targets for the reduction of total anthropogenic green house gases (GHGs) emissions. These efforts are being intensified by the Paris Agreement reached at the twenty-first session of the Conference of Parties 2015 known as the COP21 (UNFCCC, 2016).

Transport is currently one of the most energy-consuming and polluting sectors in both developing and developed countries. In the European Union (EU), for instance, it causes approximately 31% of total GHG emissions (IEA and UIC, 2012). Within this sector, metropolitan transportation is responsible for about 25% of the total CO_2 emissions (European Commission, 2011b). Additionally, high levels of air pollution and congestion are major issues related to transport in urban areas. Therefore, in a worldwide context of growing urbanisation, the implementation of efficient, reliable and environmentally friendly transport systems becomes imperative not only to meet the international agreements on GHG emissions reduction (European Commission, 2009; 2011a), but to guarantee liveable conditions in urban areas. In this vein, the EU aims to halve the use of oil-fuelled vehicles in urban transport by 2030 and eventually phase them out in urban centres by 2050 (European Commission, 2011a). Instead, cleaner metropolitan public transport systems are being strongly promoted.

Governments and inter-governmental panels have continued to highlight the scale of the problem and set tight targets to significantly reduce the impact of transport to provide clean mobility across modes and environments e.g. urban and interurban. For instance, the European Commission published the Transport White Paper in 2011 setting an ambitious goal of reducing 60% of transport-related emissions by 2050 relative to 1990 levels (European Commission, 2011c). Similar objectives have been introduced in other parts of the world. This provides the backdrop that has accelerated the need to develop viable technologies and strategies to make clean transport a reality (Roskilly *et al.*, 2015). Four main strategies have been proposed for moving to low-carbon transport while improving on other key pressing aspects of urbanisation such as accessibility and fairness: i) avoiding trips; ii) increasing energy efficiency and alternative energy sources iii) shortening trip distances iv) modal shift (Woodcock *et al.*, 2007).

Urban rail is regarded as an ideal solution to reduce the impact of urban mobility because of its great capacity, safety, reliability and excellent environmental performance (Vuchic, 2007). Urban rail systems have been gaining increasing appeal as effective and sustainable methods of mass-transport for the last decade in the EU as evidenced by the 21.7% increase in demand for the 2000-13 period measured as number of passenger-km carried compared with an average of 6.8% for the remainder of land-based transport offer (European Commission, 2015). Nevertheless, in a very competitive context where other transportation modes are considerably improving their environmental performance and the energy costs are steadily increasing, it is crucial that urban rail reduces its energy use while maintaining or enhancing its service quality and capacity (Koseki, 2010). Otherwise, urban rail may risk losing its competitive position at the forefront of economic and sustainable solutions for mobility in metropolitan areas (Nicola *et al.*, 2010).

Urban rail systems therefore play a key part in this sustainable development of metropolitan areas. This role is supported by their inherent features e.g. relatively low ratio between energy consumption and transport capacity. Nonetheless, in order to retain their environmental advantages over other transportation modes in a global atmosphere characterised by growing capacity demands and energy costs, significant improvements in energy efficiency must be achieved (González-Gil *et al.*, 2013; Powell *et al.*, 2014).

1.2. The need for improving energy efficiency

Managing a successful railway system means controlling all the interfaces between subsystems in an effective manner while ensuring human factors are considered appropriately and that the needs of the environment are respected at all times (Schmid, 2002). A systems approach is deemed essential to identify, improve and manage the environmental and energy performance of railways.

The control strategy of any system is a fundamental element to ensure it achieves its objective. For a railway system, the timetable is the control baseline. The basic measure of railway performance is the level of success in operating according to such timetable. This measure has two key dimensions i.e. punctuality (percentage of trains arriving within a given limit after a scheduled time) and reliability (percentage of trains in the timetable which ran). However, as with any business, the railway system must also be measured against the standard criteria of return on investment, incident rate, productivity and resource utilisation (Schmid, 2000). Thus, optimising energy consumption is a key strategy to improve performance and therefore competitiveness which ultimately can create the right conditions for railways to be at the core of sustainable mobility e.g. through modal shift. There is great potential for improving the performance of rail systems and increasing their sustainability (Nicola *et al.*, 2010). Indeed, urban railways (metros in particular) facilitate the integration of complex city landscapes to create sustainable cities. The decarbonisation of transport as it is currently conceived to meet the Kyoto targets depends on its electrification and the decarbonisation of the power supply to drive such electricity-dependent mobility (Anderson *et al.*, 2009). Given that urban railways are traditionally already powered by electricity, they represent a major contributor towards achieving such goals and could be seen as in alignment with long term future energy strategies (Anderson *et al.*, 2009).

Seminal work by Dincer and Rosen (2007) dissected the relationship between exergy, environment and sustainable development from a thermodynamic perspective to a more applied approach. They brought attention to the emphasis that organisations such as the United Nations have put on increasing energy efficiency to promote sustainable transport systems. In addition, this work has highlighted that potential solutions to energy-related environmental concerns have evolved in recent times to include:

- Energy conservation and increasing the efficiency of energy utilisation;
- Use of alternative energy forms and sources in transport;
- Use of energy storage;
- Optimum monitoring and evaluation of energy indicators

All these aspects have the latter point as the key enabler to provide control to the system and to enhance the success prospects for interventions pursuing the optimisation of the energy usage. Technologies and operation strategies to increase the energy efficiency of railway systems and reduce their GHG emissions have been researched in recent years (Gunselmann, 2005a; Sandor *et al.*, 2011; Meinert *et al.*, 2015; Roskilly *et al.*, 2015; Zhao *et al.*, 2015; Rupp *et al.*, 2016). Although some of the energy efficiency measures generally proposed for the rail sector may also work in urban rail, the singular characteristics of these systems seem to call for more dedicated studies. Furthermore, urban rail systems are complex environments where energy consumption is defined by a wide range of interdependent factors. Thus, a global perspective is needed ensuring that the introduction of new measures reduces the energy consumption at system-level, rather than concentrating on individual energy efficiency solutions that may compromise other aspects of the system performance (González-Gil *et al.*, 2014).

1.3. Research purpose

The overall purpose of this research is to explore how to improve energy conservation levels of urban railway systems by optimising energy usage through the application of a systemic monitoring framework. To do this, the first premise is identifying where in the system energy is being used. Only by knowing this, can appropriate technologies and strategies be implemented to maximise their effect and optimise the consumption.

A wide range of interdependent factors embracing vehicles, infrastructure and operations define energy consumption in urban rail systems. Therefore, a broad understanding of the energy flows within the system is fundamental to develop successful energy efficiency schemes. 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 technologies and strategies. Such methodology needs to exhibit a comprehensive set of energy consumption-related indicators at its core, as illustrated by Figure 1.

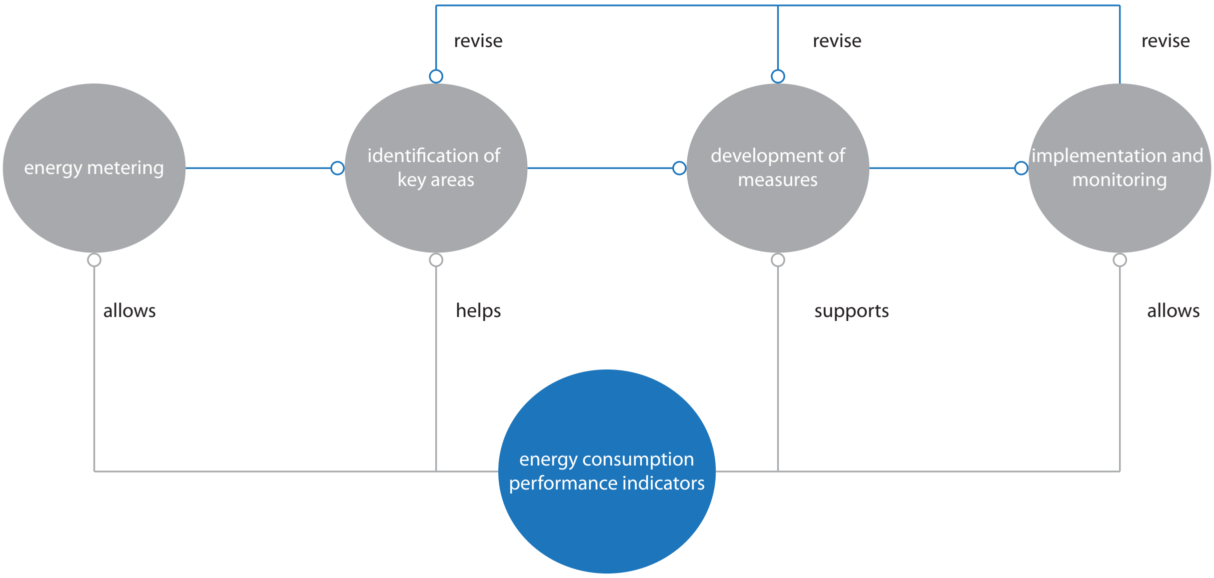


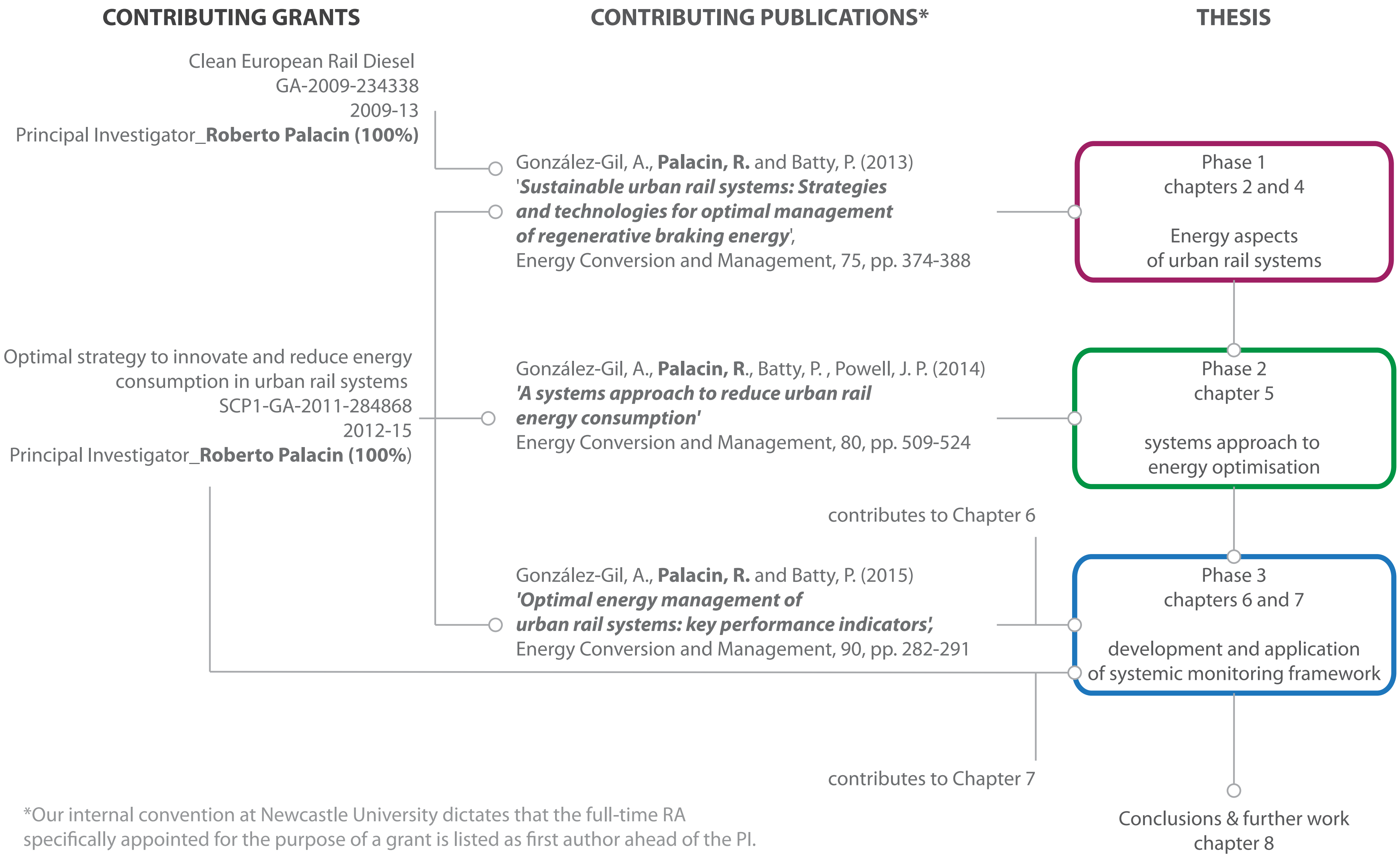
Figure 1. Simplified structure of a methodology to measure and optimise energy usage of urban rail systems.

Hence, the methodology should include a series of quantifiable parameters that allow a full understanding of the system's actual energy consumption, thus facilitating the identification of areas with a high energy saving potential. Additionally, if linked to business indicators, these energy indicators 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.

Nonetheless, the complexity of urban rail systems with a large amount of interrelated energy consumption factors that can be potentially measured makes the selection of suitable indicators 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. The research presented in this thesis is designed to address these issues and fill the knowledge gap.

1.3.1.Research context

This thesis has been framed in the context of a main research grant (EU Grant Agreement No. SCP1-GA-2011-284868) contributing to the core of this research and generating three peer-reviewed publications (see section 1.4). An additional grant (EU Grant Agreement No GA-2009-234338) has also contributed to the thesis to a lesser extent. Figure 2 shows the areas included in this thesis where these grants and publications have contributed. Figure 3 shows a timeline in relation to this doctoral work. An audit trail of the candidate's involvement as principal investigator (PI) and intellectual leader in these grants and concomitant research towards the Ph.D is available.



CONTRIBUTING GRANTS

Clean European Rail Diesel
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2009-13
Principal Investigator_**Roberto Palacin (100%)**

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SCP1-GA-2011-284868
2012-15
Principal Investigator_**Roberto Palacin (100%)**

CONTRIBUTING PUBLICATIONS*

González-Gil, A., **Palacin, R.** and Batty, P. (2013)
'***Sustainable urban rail systems: Strategies and technologies for optimal management of regenerative braking energy***',
Energy Conversion and Management, 75, pp. 374-388

González-Gil, A., **Palacin, R.**, Batty, P. , Powell, J. P. (2014)
'A systems approach to reduce urban rail energy consumption'
Energy Conversion and Management, 80, pp. 509-524

contributes to Chapter 6

González-Gil, A., **Palacin, R.** and Batty, P. (2015)
'Optimal energy management of urban rail systems: key performance indicators',
Energy Conversion and Management, 90, pp. 282-291

contributes to Chapter 7

THESIS

Phase 1
chapters 2 and 4

Energy aspects
of urban rail systems

Phase 2
chapter 5

systems approach to
energy optimisation

Phase 3
chapters 6 and 7

development and application
of systemic monitoring framework

Conclusions & further work
chapter 8

*Our internal convention at Newcastle University dictates that the full-time RA specifically appointed for the purpose of a grant is listed as first author ahead of the PI.

Figure 2. Contributions of research grants and peer-reviewed publications in the context of this thesis

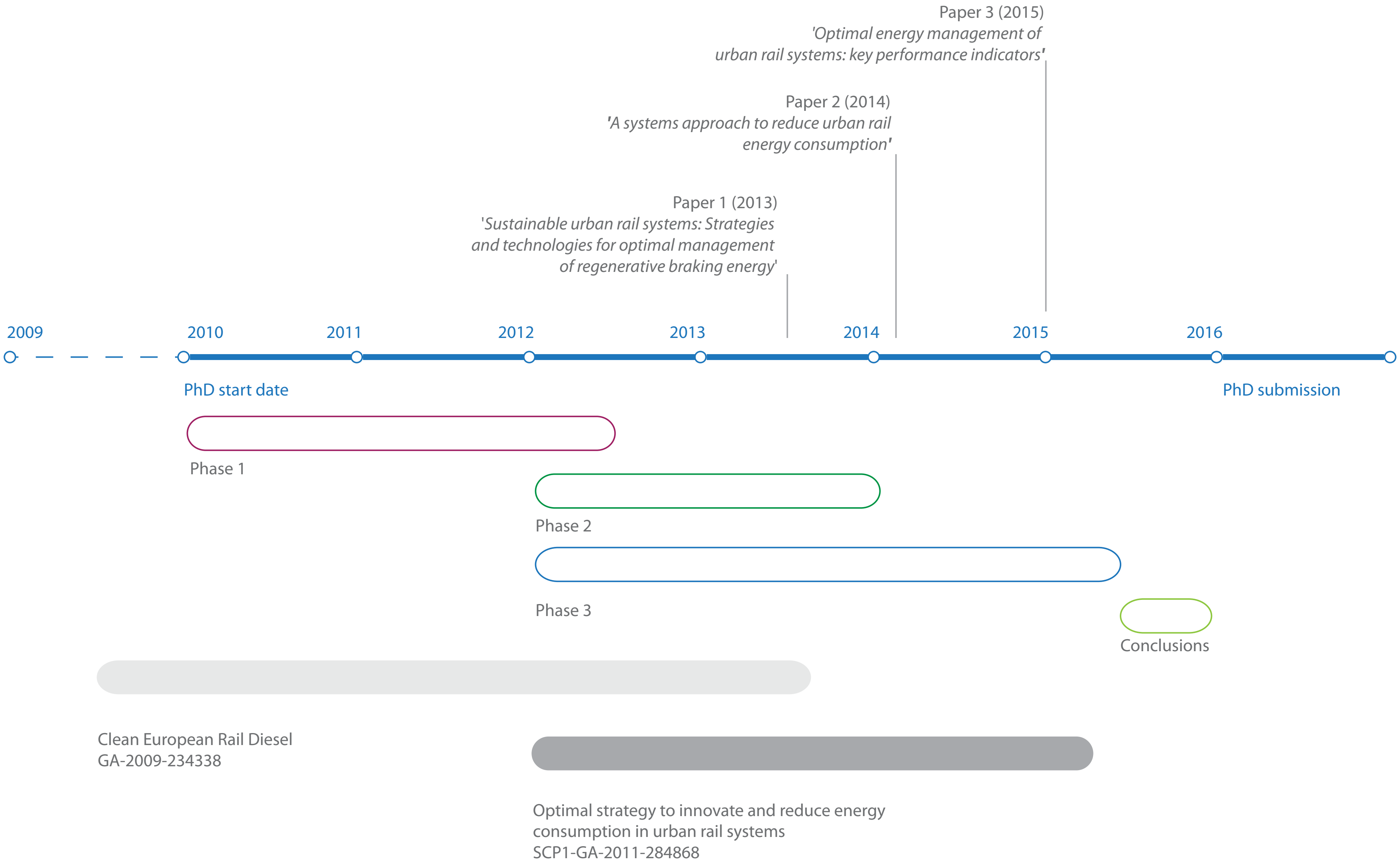

Figure 3. Timeline of thesis in relation to its research context

1.3.2. Research objectives and questions

To fulfil the purpose of this research, two objectives and three associated research questions have been defined (Table 1):

Objective	Research question	Research method	Contributing chapter(s)
Research Objective 01 (RO_01) To explore how energy is used in urban railway systems	Research Question 01 (RQ_01) Which are the key energy flows influencing consumption at system, sub-system and component levels?	Qualitative	2 & 4
Research Objective 02 (RO_02) To develop a holistic monitoring framework for energy optimisation of urban railway systems	Research Question 02 (RQ_02) Are current approaches to energy efficiency and monitoring suitable for system-wide optimisation?	Qualitative	5
	Research Question 03 (RQ_03) Could an adaptable multi-level monitoring framework provide a realistic systems perspective on energy performance of urban railways?	Qualitative and quantitative	6 & 7

Table 1. Research objectives and associated research questions

Figure 4 shows how these objectives, research questions and the thesis chapters interact.

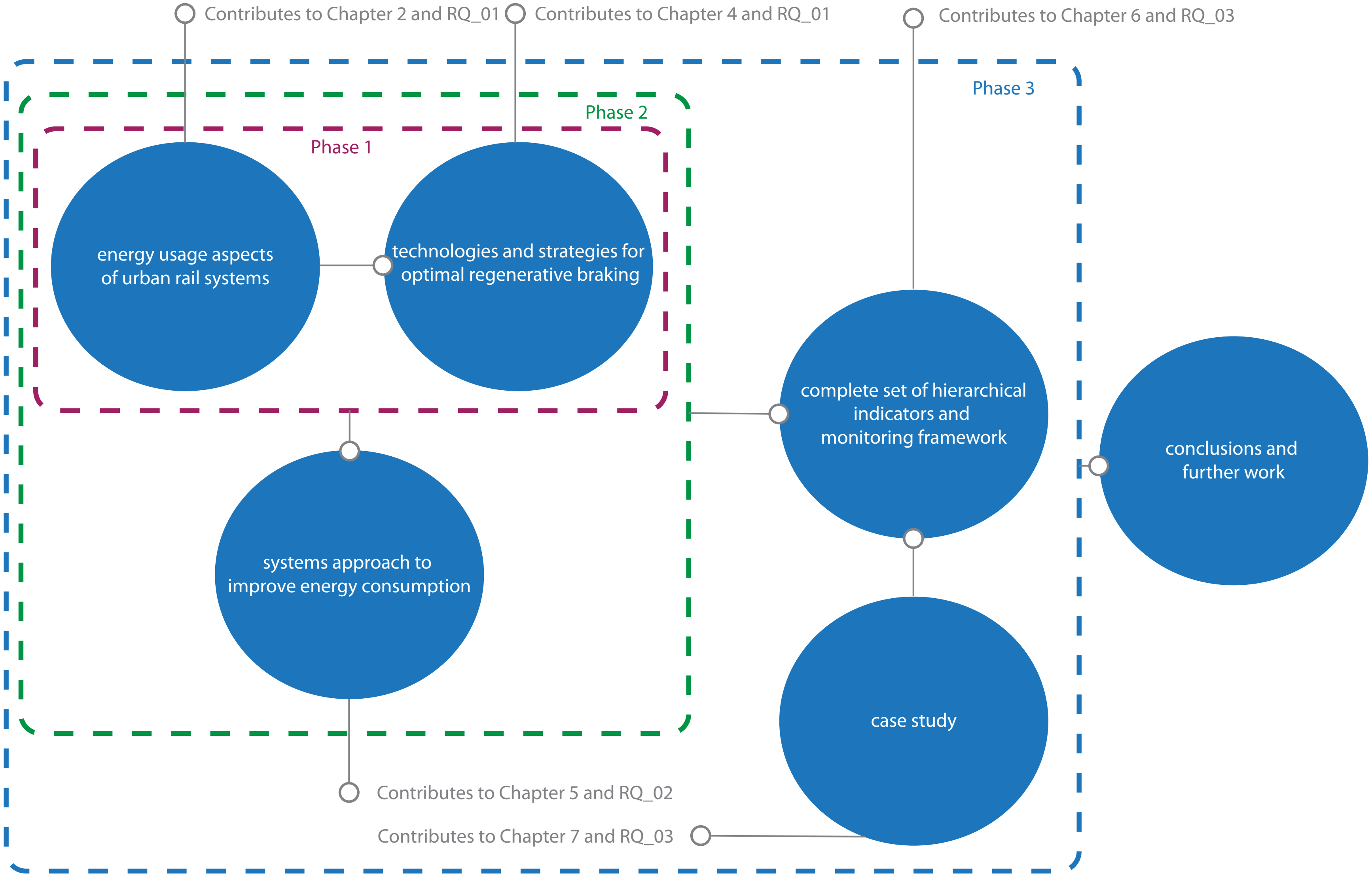

Figure 4. Thesis structure and interactions with chapter

1.4. Contributions

In addressing its research objectives and related questions, the thesis attempts to provide a structured response to the need to improve the overall energy efficiency and performance of urban rail systems. These improvements facilitate the enhancement of competitiveness allowing for a more prominent role for urban rail systems in shaping mobility in 21st century cities while at the same time contributing to meeting the stringent GHG emissions targets associated with the effects of climate change. Specifically, the contribution to knowledge provided by this research can be summarised as follows:

1. An understanding of how and where energy is being used in urban railway systems;
2. A comprehensive assessment of existing technologies and strategies suitable for optimising energy consumption of urban railways;
3. A comprehensive description of the systems dimension of energy usage in urban railways;
4. The definition of a complete set of indicators (i.e. key performance indicators and performance indicators) applicable at all levels (i.e. system, sub-system);
5. The definition of a monitoring framework and associated methodology based on the indicators created, supporting the appraisal of interventions and leading to energy efficiency improvements

Importantly some of the novel contents of this thesis have already generated three peer-reviewed manuscripts[1] published in Elsevier's International Journal for Energy Management and Conversion, a quartile 1 (Q1) publication. These publications form the basis for Chapters 4, 5 and 6:

González-Gil, A., Palacin, R. and Batty, P. (2013) 'Sustainable urban rail systems: Strategies and technologies for optimal management of regenerative braking energy', *Energy Conversion and Management*, 75, pp. 374-388;

González-Gil, A., Palacin, R., Batty, P. and Powell, J. P. (2014) 'A systems approach to reduce urban rail energy consumption', *Energy Conversion and Management*, 80, pp. 509-524;

González-Gil, A., Palacin, R. and Batty, P. (2015) 'Optimal energy management of urban rail systems: Key performance indicators', *Energy Conversion and Management*, 90, pp. 282-291.

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[1] Our internal convention at Newcastle University dictates that the full-time RA employed specifically for the purpose of a research grant is listed ahead of the PI.

1.5. Thesis structure

This thesis is organised into eight chapters. This Chapter 1 introduces the overall motivation for the research, including the objectives and associated research questions. Chapter 2 describes urban rail systems energy aspects including optimisation by analysing the existing literature. Chapter 3 discusses several methodological approaches leading to the selection of the most appropriate for the research conducted. Chapter 4 investigates the merits of regenerative braking as a core area for improving energy efficiency, comprehensively examining strategies and technologies for the optimal management of such approach. Chapter 5 defines a systems approach to improve energy consumption of urban railways using a range of technologies and strategies. A proposed methodology to evaluate and optimally implement energy efficiency measures completes this chapter. A complete set of original energy-consumption key performance indicators (termed KEPIs) is described in Chapter 6. These hierarchical indicators form the core of the adaptable monitoring framework proposed. Five cases illustrating how to apply this framework in different urban rail systems are presented in Chapter 7. Chapter 8 provides the overall conclusions and contribution of the research as well as suggestions for further work.

It is worth noting that the literature review is presented in two different chapters (2 and 4). The rationale for this approach is based on the logical sequential outlook of the overall thesis, which is also reflected in the joined-up nature of the research objectives and questions introduced in this Chapter 1 (section 1.3.2).

At first and prior to defining the research methodology and design (Chapter 3), a comprehensive literature review is needed to i) characterise urban rail systems describing their main features and determining the main energy flows within the system; ii) identify state-of-the-art advances to reduce energy optimisation in urban rail systems, assessing their target and impact areas/sub-systems; iii) describe, assess and analyse energy management systems and their applicability to urban rail systems. These three aspects provide the necessary evidence underpinning the thesis aim outlined in this Chapter 1 and constituting the background to the research and its purpose as described in sections 1.2 and 1.3. Hence, Chapter 2, which contains this first part of the literature review, is an essential step before proceeding with the research design process in Chapter 3 as it substantiates the existence of a gap in the knowledge.

Once the research design has been defined (Chapter 3) including the methodological framework and techniques to be used, next Chapter 4 continues the literature review and focuses on the specifics of regenerative braking as an approach to achieve higher levels of energy conservation in urban rail systems. This second part of the literature focuses on this more distinct topic identifying, describing and assessing interventions of a strategic and technological nature for the management of regenerative braking in urban rail systems. Regenerative braking is widely regarded as a key feature of urban rail systems and one that can have a pivotal role in their overall energy performance. Therefore, this part of the literature review completes the essential background assessment that supports the overall thesis; it requires a separate chapter as it explores in depth a significant number of aspects related to interventions related to a specific application area rather than the review of the fundamental assumptions driving the thesis.

Chapter 2- ENERGY ASPECTS OF URBAN RAILWAY SYSTEMS

2.1. Urban rail systems characterisation

Prior to exploring the energy aspects of urban rail systems, a clear perspective of what is understood by this term and their main characteristics needs to be determined. The term *urban rail systems* or *urban rail transport* generally refers to railway systems providing public transport services within metropolitan areas. Schmid *et al.* (2015) intuitively defined urban rail systems as "a system that runs a frequency such that the passenger does not require a timetable".

The sharp increase in the size of cities during the late 1800s meant that they were able to support the operation of railway services within their own boundaries and hence, urban rail systems were born (Schmid *et al.*, 2015). These started as what today is known as tram and light rail systems in the form of high-wheeled coaches with the entrance at the back (i.e. an *omnibus,* first introduced in London) running on rails and drawn by horses (1820s France) with the electrified version rapidly being taken up by cities from first introduction in 1881 in Berlin (Siemens & Halske) and 1883 in Bristol. As congestion increased, new routes had to be built below the surface becoming the early metros or subways (Gray and Hoel, 1992; Vuchic, 2007; Schmid *et al.*, 2015).

There has been a long and on-going debate on the nomenclature of the different types of urban rail systems and what they actually mean. Despite semantics, there are four distinct variants of urban rail systems i.e. tramways, light rail, rapid transit and suburban systems, all based on the concept of right of way or ROW (e.g. Vuchic, 2005; 2007) or perhaps more commonly know as segregation levels (e.g. Schmid *et al.*, 2015). Vuchic (2005; 2007) distinguished three categories of right of way, namely "A" as fully separated or segregated system, "B" as a partially separated one and "C" a street-based system mixed with traffic. Table 2 summarises these types of urban railways based on their right of way, capacity at peak time measured as passengers per hour per direction (PPHPD) and the volume of passengers carried per single carriage. Figure 5 shows illustrative pictures.

Urban rail system	ROW	PPHPD	Passengers per vehicle
Tramway, tram, streetcar	C	4,000-12,000	100-200
Light rail transit, light rail, light metro	A, B	6,000-20,000	110-250
Rapid transit, heavy metro, metro, subway	A	10,000-40,000	140-280
Suburban, regional	A	8,000-35,000	140-210

Table 2. Typical characteristics of different types of urban railways (Schmid, 2000; Vuchic, 2007; Schmid *et al.*, 2015).

ROW A_
Fully segregated

ROW B_
partially segregated

ROW C_
street-based and
fully mixed with traffic

Figure 5. Examples of different urban rail systems according to their right of way (A, B or C) design

Contemporary light rail systems can be generally described as medium capacity urban railways using routes that are either integrated with street traffic (e.g. trams) or partially separated from it (e.g. light rail transit or LRT). These are usually powered by 600 V or 750 V direct current (DC) overhead wires. Light metro systems operate on segregated lines under normal railway regulation and operating at surface level, underground, elevated or a mix. Traction supply tends to be 600 V, 750 V or 1,500 V DC overhead or third rail. The Tyne & Wear Metro was one of the first such systems to be introduced in the world. Heavy Metros are high capacity wholly segregated systems built to rigorous standards and are the hallmark of many iconic cities around the world (e.g. London, Paris, Tokyo, New York, Moscow). Traction is commonly third rail with some overhead systems at 1,500 V DC although alternating current (AC) traction has been introduced in some systems in recent years e.g. New York. Suburban railways use mainline rail routes and operate under such mainline standards although the operation style is closer to that of an urban system (Schmid *et al.*, 2015).

Irrespective of the type of rail system, the operating urban environment has as main distinguishing feature the short distance between stations/stops. This singularity dictates the operational design and timetable configuration with duty cycles characterised by high acceleration and braking rates, particularly on the segregated types (e.g. Metro). Single train movement has been described considering either three basic modes i.e. motoring, coasting and braking (Bocharnikov *et al.*, 2007) or four i.e. acceleration, cruising, coasting and braking (Hansen and Pachl, 2008; Powell and Palacín, 2015a; b). Their usage varies but for instance, coasting might not be considered if operations are designed to target absolute minimum run time (Hansen and Pachl, 2008). Figure 6 shows a typical profile of a single train run using all four phases and the associated implications for energy usage.

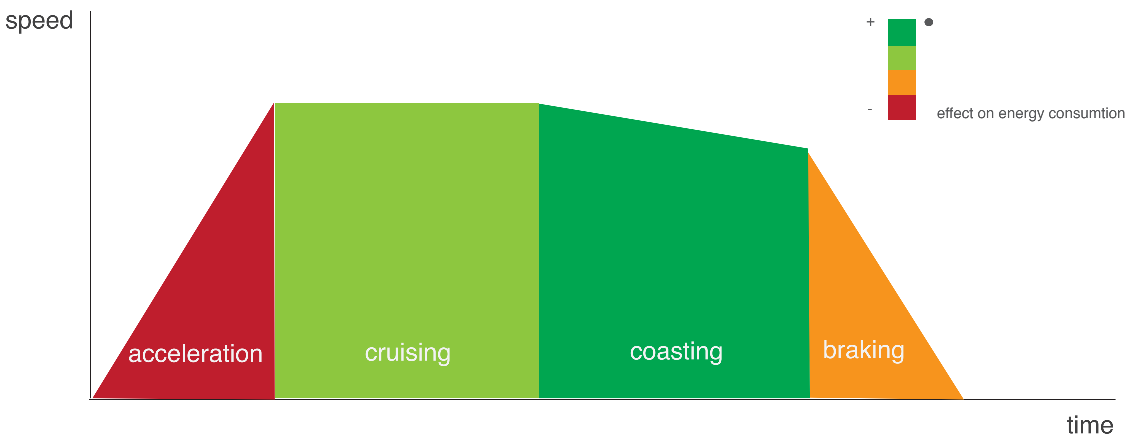

Figure 6. Typical four operational phases for train movement and associated energy effects

Rapid rail transit (RRT) or Metro systems have the greatest level of service, operating approximately 3.5 million passenger-kilometres annually in Europe alone

(UITP and ERRAC, 2009). This high level of patronage also applies to other parts of the world. For instance, it is estimated that around 360 million people worldwide use metro and tram services daily representing abut 30% of all public transport trips even if this type of urban rail systems is only available in around 400 cities (Dauby, 2015). With the exception of some regional rail systems utilising diesel traction (which are out of the scope of this work), all urban rail systems are electrically powered. Consequently, urban rail is characterised by presenting a high performance of operation, low levels of noise and absence of local air pollution. Other distinguishing features that make urban rail a very appealing option to improve passengers' mobility in urban areas are:

- Relatively low land use requirements;
- High capacity and frequency of services;
- Possibility of various levels of automation including full driverless operation;
- Very high degree of safety and punctuality;
- Widespread acceptability linked to a strong image and identity attracting passengers.

Nevertheless, a major handicap for urban rail systems is in the higher investment cost typically required when compared with non-rail transport modes. However, despite the extensive contributions to the discourse found In the literature on the financial merits of investing in urban railways (e.g. Simpson, 1989; Black, 1993; Huang, 1996; Hass-Klau and Crampton, 1998; Richmond, 1998; Mackett and Babalik, 2001; Babalik-Sutcliffe, 2002; Hass-Klau *et al.*, 2003; Mackett and Sutcliffe, 2003; Olesen, 2014) there is continuous strong political and public support for such systems, as Babalik-Sutcliffe (2002) illustrated with this extract of the Environment, Transport and Regional Affairs Committee of the UK's House of Commons (Select Committee on Environment Transport and Regional Affairs, 2000):

> *"If the Government believes that it is important to attract motorists out of their cars, alternative forms of public transport must be put in place first. As the evidence shows, people will not switch to public transport unless it is reliable, frequent, efficient, safe and clean with affordable fares. Light rapid transit systems meet these criteria, and so, where appropriate, they should be pursued."*

2.2. Energy use in urban rail systems

Energy use in urban rail systems may be typically classified into two broad but clear categories: traction and non-traction consumption. Traction consumption accounts for the energy used to operate the rolling stock across the system comprising the vehicle propulsion itself as well as powering its auxiliary systems in service mode. Non-traction, in turn, refers to the energy utilised to power other sub-systems and components e.g. stations, depots, signalling.

2.2.1.Traction energy consumption

Railways in general use non-autonomous (e.g. electrified) propulsion systems as well as autonomous systems (e.g. diesel) with the former being commonly found in non-urban systems. This influences their environmental impact as, in the case of non-autonomous propulsion, it becomes dependent of the energy mix of a given country (Roskilly *et al.*, 2015). On average, traction energy generally represents between 70% and 90% of the total energy consumption in urban rail systems, of which around 20% is due to on-board auxiliaries (González-Gil *et al.*, 2014; Powell *et al.*, 2014). Hence, the majority of recent advances to reduce energy consumption in railway systems have focused on the traction system itself (Powell *et al.*, 2014), primarily by using regenerative braking (González-Gil *et al.*, 2013), applying energy-efficient driving strategies (e.g. De Martinis *et al.*, 2013), or improving the propulsion chain efficiency (e.g. Kondo, 2010). This is also in line with the three approaches to energy optimisation in urban rail systems operation proposed by Oettich *et al.* (2004) i.e. driving style and timetable, regenerative braking and adapting supply to demand in a flexible way.

Unlike autonomous traction, where the energy required for train operation is generated within the vehicle itself, electric traction requires an external power supply system. In general, these types of electric systems can either work with direct current (DC) or alternating current (AC). Notwithstanding, most urban rail systems worldwide are DC-powered, either at 600/750 V (e.g. trams), 1500 V (e.g. light metro) or 3000 V (e.g. suburban). Regardless of the type of electrification, railway power supply networks essentially consist of the following subsystems as described in Table 3.

Power supply network subsystem	Description
Substations	Allocated at predetermined places along the track, they include step-down transformers to condition the power from the distribution network, which can be the public grid or a distribution network within the system itself. In the case of DC electrification, substations are additionally equipped with a rectifier assembly to convert AC into DC.
Traction power distribution system	It conveys the electric power from the substations to the rail vehicles. It typically consists of an overhead line (catenary), though a conductor rail (third rail) can be also found in some metro systems with heavy traffic loads and/or reduced space inside tunnels.
Traction power return system	It returns the electric power to the substations, typically through the running rails or an extra (fourth) conductor rail

Table 3. Brief description of railway power supply network sub-systems

Rail vehicles are directly fed from the power distribution system by means of pantographs or current collector shoes, depending on whether the electricity is supplied through overhead lines or conductor rails, respectively. Within the rolling stock itself, electricity is used to drive both the traction equipment and the auxiliary systems. The auxiliaries consist of all the equipment assuring the operation of the vehicle e.g. traction cooling systems, compressors. Furthermore, auxiliaries include the passengers' comfort functions, i.e. heating, ventilation and air-conditioning (HVAC), lighting and information systems. In turn, the propulsion system comprises the electric traction drive, including its associated equipment (converter and control system) and the torque transmission system. As for the type of traction motors, DC machines have traditionally been the most widely used in urban rail. However, as a result of the outstanding advances experienced by power electronics in the last decades, AC (usually asynchronous induction) motors have been widely introduced, as they typically require less maintenance work, offer lighter weight per output torque and present higher efficiency (Matsuoka and Kondo, 2010). Figure 7 illustrates a typical DC power supply network for urban rail systems.

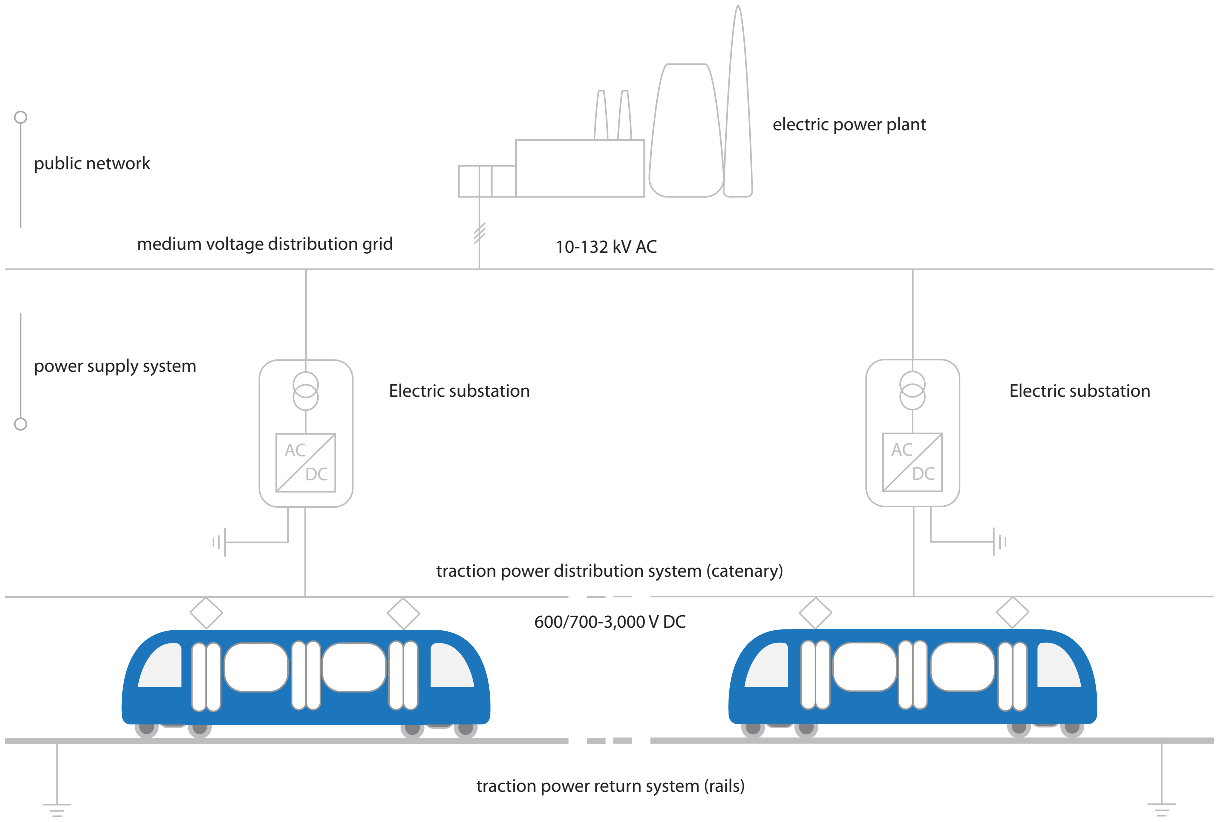

Figure 7. Diagram of a typical urban rail DC power supply network

The literature contains a number of measured and estimated consumption data for different types of urban railway systems. In order to illustrate a typical traction energy flow and given the significant variation between systems, the *Sankey* diagram in Figure 8 has been created from a selection of works in the literature (Gunselmann, 2005a; Struckl *et al.*, 2006; Steiner *et al.*, 2007; Chymera *et al.*, 2008; Henning, 2008; Barrero *et al.*, 2010; Ortega and Ibaiondo, 2011a; Chymera, 2012; García Álvarez and Martín Cañizares, 2012b) to exemplify rather than represent the proportion of energy consumed by different traction subsystems in urban railways. *Sankey* diagrams are widely used in the literature in disciplines such as industrial ecology to represent energy balances of complex systems (Schmidt, 2008b; a) making them ideal for the purpose of portraying traction energy flows.

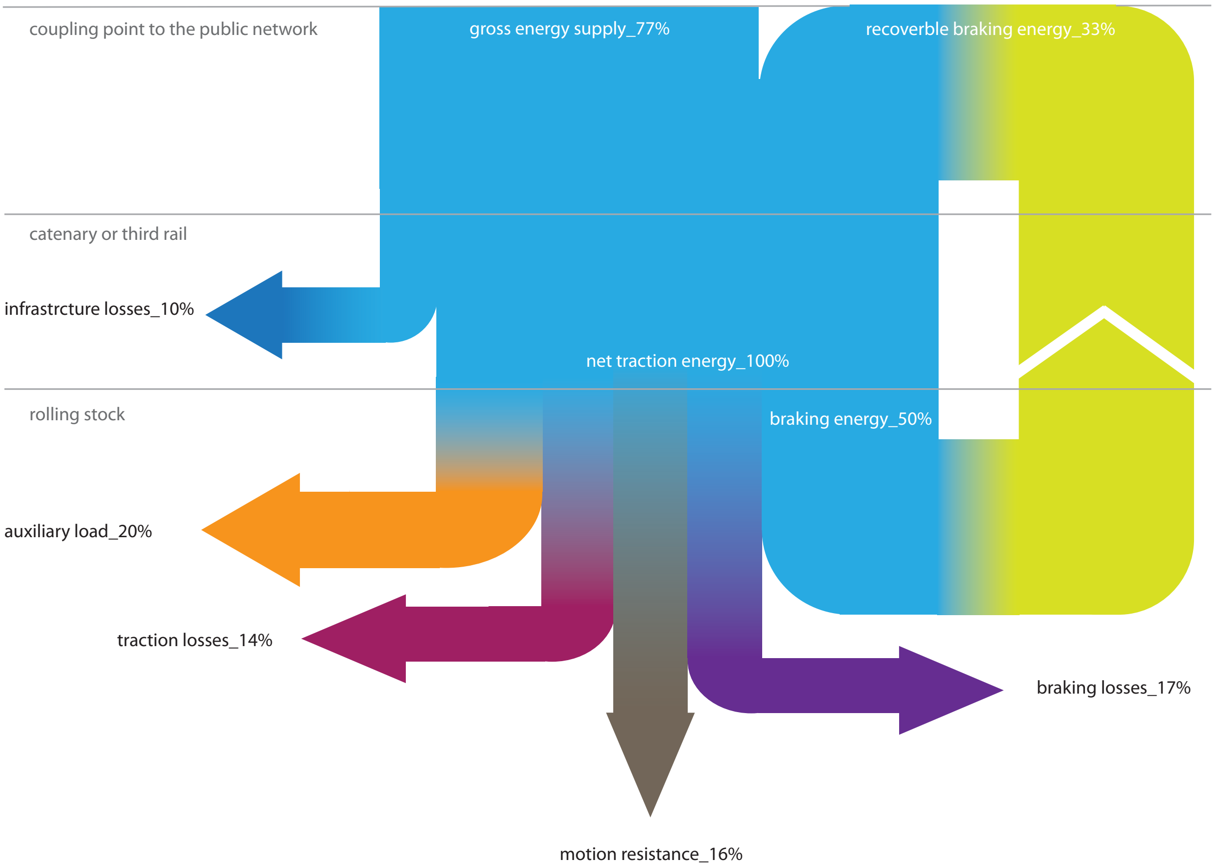

Figure 8. Sankey diagram depicting a typical traction energy flow in urban rail systems

Infrastructure losses in this figure refer to the electric losses occurring from the point of common coupling to the pantograph or collector shoes in the case of third/fourth rail) which translate as the electric losses in the substations and the distribution network, the latter being significantly higher (Chéron *et al.*, 2011). Infrastructure losses principally depend on the voltage level of the rail system and its traffic load, being more important for low voltage networks with heavy traffic. Additionally, in *coupled through* systems, where several electric sections of the line are connected to favour the regenerative energy transfer between vehicles, the electric losses are also higher (Steiner and Scholten, 2006). Typical values for infrastructure energy losses can be as high as 22%, 18%, 10% and 6% for 600 V, 750 V, 1,500 V and 3,000 V DC networks, respectively (Pilo De La Fuente *et al.*, 2008; Takagi, 2010).

The Sankey diagram also shows that auxiliary systems consume an important share of the total energy entering the rolling stock. HVAC equipment is generally responsible for the most significant share of this consumption, which is strongly influenced by the climate conditions (Anderson *et al.*, 2009). For instance, heating systems account for 28% of the total traction energy in Metro Oslo (Struckl *et al.*, 2006), whereas all auxiliary systems represent about 10% of the total vehicle consumption in London Underground (Chymera, 2012).

The traction energy flow illustration identifies another major share of such energy is dedicated to overcoming the motion resistance of the rolling stock. This comprises both aerodynamic opposition to the vehicle movement and mechanical friction between wheels and rails. Aerodynamic drag increases with the square of velocity, therefore its influence is more noticeable in segregated mass capacity systems (e.g. Metro and Suburban railways) than in systems with ROW C or B e.g tramways. In turn, mechanical resistance plays a more decisive role in low-speed services, the mass of the rolling stock being the main parameter to take into account for reducing its effect. It can be concluded from the available literature that, on average, motion resistance is responsible for approximately 16% of the traction energy use in urban rail services (Gunselmann, 2005b; Struckl *et al.*, 2006; Chymera, 2012; García Álvarez and Martín Cañizares, 2012b).

Inefficiencies in the converters, electric motors and transmission system are responsible for the majority of the energy losses in the traction chain. The efficiency of these components may significantly vary across the speed and power ranges, and so the overall values will depend on the specific duty cycle. García Álvarez and Martín Cañizares (2012b) estimated that the efficiency of converters is about 98.5–99.5% while the efficiency of motors is approximately 90-94% for DC motors and 93-95% for the induction variant. Losses in the gear system are evaluated to be 2–4%.

Further assessing the Sankey diagram (Figure 8) it can be observed that the greatest portion of traction energy is wasted in braking processes. The amount of energy dissipated in braking strongly depends on the type of urban rail system (e.g. tram, LRT, Metro, Suburban), but it can be considered to account for approximately half of the energy entering the rolling stock. This rate clearly increases with the frequency of stops, being higher in tramways and metros than in suburban rail systems, for instance. It is possible to recover and reuse a significant proportion of the braking energy provided that electric motors can act also as generators while braking. In contrast, about one third of the braking energy is irreversibly lost due to the use of friction brakes and the losses occurring in motors, convertors and transmission system during dynamic braking.

2.2.2.Non-traction energy consumption

The term non-traction energy consumption embraces all of the energy utilised by different sub-systems and services other than rolling stock ensuring the proper operation of urban rail systems. These typically comprise control & command (e.g. signalling), passenger stations, depots and other infrastructure-related components e.g. tunnel ventilation fans, groundwater pumps, and tunnel lighting. Even though the vast majority of non-traction services are electricity-powered, it is also possible to find some diesel or gas-fired heating systems in stations and depots (Transport for London, 2009; Fuertes *et al.*, 2012).

Stations, and particularly underground stations, are complex sub-systems that integrate both mobility and commercial services and where human and comfort aspects are of great importance (Ordódy, 2000; Awad, 2002; Ampofo *et al.*, 2004a; Abbaspour *et al.*, 2008; Mugica-Álvarez *et al.*, 2012). The main energy-demanding facilities at stations typically include HVAC, lighting, escalators, moving walkways, lifts and information displays (Hong and Kim, 2004). In subway stations, the HVAC equipment is generally responsible for the greatest energy consumption, particularly air conditioning and ventilation where the energy demand may represent up to two thirds of the total consumption (Zhang and Wei, 2012). Stations also contain a significant amount of thermal loads attributable to passengers, heat transfer from the ground, electrical equipment and train operation in tunnels e.g. braking heat, electrical losses (Wang *et al.*, 2011; Leung and Lee, 2013).

Energy in depots is mainly consumed by activities related to inspection, maintenance and cleaning of rolling stock (de Wilde d'Estmael *et al.*, 2013). These processes also imply energy consumption from auxiliary systems of the vehicle e.g. lighting or HVAC. Rolling stock stabling includes both hibernation periods and pre-heating or pre-cooling operations meaning that vehicle comfort systems consume a non-negligible amount of energy while parked at depots (CENELEC, 2013).

The non-traction energy share in urban rail systems strongly depends on whether the system is underground or surface operated, and also on the climatic conditions. Thus, the non-traction energy consumption in a tramway system is minor, whereas it accounts for approximately one third of total energy use in metro systems on average (Fuertes *et al.*, 2012). The lack of published data on the energy consumed by non-traction subsystems makes it difficult to provide generalised figures for urban rail systems. However, to illustrate the order of magnitude of these consumptions, Figure 9 shows the specific case of London Underground (Transport for London, 2009).

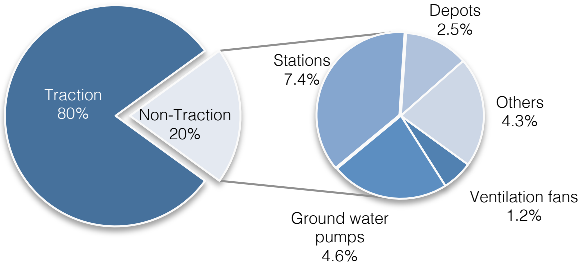

Figure 9. Distribution of non-traction energy in London Underground.

Here, stations consume about 37% of the total energy destined for non-traction purposes (7.4% of the total energy consumed in the system), while operations in depots account for 12.5% and tunnel ventilation fans for 6%. Especially noteworthy is the high energy consumption of ground water pumps, about 23% of the non-traction energy demand.

2.3. Identification, measurement and monitoring of energy usage

Energy efficiency is not considered a goal in itself but a means to an end of overall efficient resource allocation (Jaffe and Stavins, 1994). This could be interpreted as an enabler for systems-wide resource efficiency. Energy efficiency could be defined as "*using less energy to produce the same amount of service or useful output*" (Patterson, 1996). This broadly translates to the following ratio:

$$\frac{useful\ outcome\ of\ a\ process}{energy\ input\ into\ a\ process}$$

Hirst and Brown (1990) described the gap between the current levels of energy efficiency and the optimum levels that could be achieved. More recently, Backlund *et al.* (2012) referred to an extended energy efficiency gap whereby if energy management approaches were used in addition to cost-effective technologies, the levels of efficiency could be enhanced. Energy efficiency changes require the use of indicators to monitor such fluctuations. These can be categorised into four different groups as described in Table 4 below.

Type of Indicator	Description
Thermodynamic	These indicators are based entirely on measurements derived from the science of thermodynamics. They can be ratios or more sophisticated measures relating actual and ideal energy usage.
Physical-thermodynamic	A hybrid indicator where the input and outputs are measured in thermodynamic and physical units respectively. The physical units attempt to capture the service delivery process e.g. passenger-km.
Economic-thermodynamic	Another hybrid indicator group where the output is measured in economic units, usually market prices.
Economic	This group of indicators measure efficiency in terms of market prices only.

Table 4. Categories of energy efficiency indicators according to Patterson (1996)

Thermodynamic indicators have the attraction to provide a clear, transparent and unbiased measure of a given process/output in the context of its particular environment where is operating e.g. temperature (Patterson, 1996). This offers traceability and monitoring capacity when the surrounding physical conditions evolve, modifying the energy efficiency accordingly.

Nevertheless, perhaps the most relevant and suitable indicator for rail systems and public transport systems in general is the physical-thermodynamic category. This type of indicator captures the service and end user perspective as part of the output measurement. A typical physical measure for transport systems would be the number of passengers (or tonnage) per kilometre, which as Patterson's work indicates, allows for time series analysis, adding to their suitability for transport systems. This is further corroborated when it indicates that "If hybrid physical-thermodynamic indicators are to be used […] it is appropriate that they are developed on a sectoral basis " which provides further evidence of their suitability for public transport systems and in the case of this thesis, urban rail systems.

Energy management is a relatively common practice in industrial activities with a particular focus on supervision of costs associated with energy usage in plants and other buildings (Gordić *et al.*, 2010). Examples of this sort of research include automotive plants and energy-intensive sectors such as steel, paper and petro-chemicals (Schulze *et al.*, 2016)

All of these procedures use an energy audit as a basic step towards implementing effective management structures. An energy audit can be defined as "a process to evaluate where a building or plant uses energy and identify opportunities to reduce consumption" (Thumann and Younger, 2003).

Schulze *et al.* (2016) have provided an extensive and thorough systematic review of the existing literature addressing energy management in industry. This work offers an interesting parallel between the energy efficiency challenges faced by industry and those of public transport systems. There are remarkable similarities between the difficulties in improving energy efficiency given the structural complexity of industrial energy systems, the strong need for a systematic approach to the management of energy use in the sector and the equivalent (or perhaps even higher) complexity of urban rail systems. The authors underline the lack in the literature of a clear comprehensive conceptual framework of energy management for industry as well as a consistent understanding of what energy management is. It suggested that energy management involves five dimensions, namely: (i) strategy/planning; (ii) implementation/operation; (iii) controlling; (iv) organisation; (v) culture. Regarding the implementation/operation dimension, three themes emerge from the authors' assessment of the existing literature: Implementation of energy efficiency measures, investment decisions on such measures and energy auditing.

Energy auditing, also termed energy analysis or energy evaluation (Schulze *et al.*, 2016), can be described as a formal and systematic method to assess existing energy flows with the aim to identify actual consumption patterns, quantify the usage associated with them and judge the potential to improve energy efficiency (Gordić *et al.*, 2010; Abdelaziz *et al.*, 2011). These audits can be categorised into preliminary, general and detailed audits, as briefly described in Table 5.

Type of audit	Description
Preliminary audit	The simplest type of audit involving a brief review of billing and operational data plus minimal interviews with relevant staff
General audit	An extension of the preliminary audit comprising a more detailed collection and examination of data available by for instance incorporating additional metering of specific energy flows
Detailed audit	An extension of the activities included in the general audit by providing a dynamic model characterising energy usage e.g. identifying load profiles over different time horizons

Table 5. Types of energy audits and their main characteristics according to Abdelaziz *et al.* (2011)

A model is understood here as an approximate representation of reality which is considered to have a significant value for “abstracting the essence of the subject of enquiry, showing interrelationships and facilitating analysis” (Hillier and Hillier, 2011). Schulze *et al.* (2016) also identified three themes associated with the existing knowledge related to energy performance management: (i) energy accounting, (ii) performance measurement and (iii) benchmarking.

Bunse *et al.* (2011) stressed the need for energy efficiency monitoring and constant analysis of consumption as an important basis for energy management allowing for the identification of improvement prospects in addition to observing the effects of decisions made in relation to energy usage. This is aligned with monitoring practices. For instance Kannan and Boie (2003) corroborated this by establishing that monitoring energy consumption supports the decision of whether expected energy savings are achievable or not. Furthermore the literature e.g. (Rohdin and Thollander, 2006; Thollander and Ottosson, 2010) suggests that complex industrial organisations with multiple divisions fail to allocate properly the associated energy costs. Monitoring systems are proposed where sub-metering and facility level effectively provide appropriate energy cost allocation (Thollander and Ottosson, 2010). The previously alluded to simile between complex industrial structures and the level of complexity of public transport systems (e.g. urban rail systems) is also applicable to this reasoning. The multiple divisions and sub-metering at facility level are analogous to the urban rail sub-systems (e.g. infrastructure) and its individual components (e.g. stations, depots).

Performance measurement is considered an integral part of energy management with the definition and application of key performance indicators (KPIs) as a central component at the core of such approach (Schulze *et al.*, 2016). These indicators tend to be expressed in the form of activity output versus energy input ratio. However, complexity of systems and structures result in an extensive variety of indicators e.g. economic, physical, thermodynamic and hybrid (Bunse *et al.*, 2011). Recent empirical studies by Sivill *et al.* (2013) and Virtanen *et al.* (2013) concluded that commonly used data and indicators in energy-intensive industries do not facilitate effective performance evaluation and decision support. This supports the research outcomes by Bunse *et al.* (2011) arguing that suitable KPIs for energy efficiency should be defined at company, plant and process levels. The analogy complex industrial systems-complex public transport systems applies once again to these findings where company, plant and process levels can be translated as system (e.g. urban railways), sub-system (e.g. infrastructure, stations) and component (e.g. escalators) levels. In turn, this can be interpreted as evidence of the need for a whole systems approach to performance measurement using indicators as a response to the lack of research available in the literature.

Benchmarking is the third predominant theme in the literature related to energy performance management (Schulze *et al.*, 2016). Table 6 summarises three types of energy efficiency benchmarking according to Peterson and Belt (2009)

Type of Benchmark	Description
Industry benchmark	A process of comparing own performance with that of other companies (e.g. competitors). A challenging approach given the difficulty of accessing sensitive data from other companies.
Historical benchmark	A comparison of actual energy consumption of a facility or process within the company against the records at an earlier time.
Company-wide benchmark	A comparison of several facilities and processes within a given company. The so-called “top quartile analysis” is a good approach to this type of benchmarking where after a ranking process the performing top 25% is used as the level to be achieved by the low performing units.

Table 6. Types of energy efficiency benchmarking according to Peterson and Belt (2009)

Several studies have emphasised the lack of method and criteria for effective comparison between competitors (Bunse *et al.*, 2011; Ke *et al.*, 2013) although benchmarking is considered a very useful tool for understanding energy usage patterns at a given facility prior to optimising them (Worrell and Price, 2006; Schulze *et al.*, 2016). A number of possible methods have been suggested in the literature e.g. specific energy consumption and energy efficiency index (Stawicki *et al.*, 2010), a tailor-made benchmarking tool for heavy industry plants (Worrell and Price, 2006), data envelopment analysis (DEA) (Önüt and Soner, 2007) and a matrix-based approach (Giacone and Mancò, 2012). Benchmarking energy performance of urban rail systems has been carried out at all three levels although there is no evidence of a systems approach to this but instead it is sporadic and of the sub-system or component level. The work of Anderson *et al.* (2009) is perhaps the most relevant but unfortunately it is associated with the activities of CoMET (Community of Metros) and Nova metro benchmarking groups[2] and their results and methods remain largely confidential.

The literature indicates that industrial organisations have not achieved yet the large unexploited energy efficiency potential they have (Backlund *et al.*, 2012). Schulze *et al.* (2016) suggests that energy management is an essential approach to advance the closure of the efficiency gap and encourages the implementation and maintenance of energy efficiency measures. Energy auditing, monitoring using KPIs and benchmarking are fundamental for energy management approaches aiming at reducing the efficiency gap.

2.4. Performance and the use of indicators for urban rail systems

Oettich *et al.* (2004) proposed that energy optimisation for operation of urban rail systems can be achieved through approaches focused on driving style and the timetable, regenerative braking and adapting supply to demand in a flexible way. This is also echoed by other authors e.g. (Powell *et al.*, 2014). The hierarchic model of urban operation optimised train control introduced by Oettich *et al.* (2004) offers a good structured approach to energy usage from an operational perspective also classifying the three strategies in terms of timescale for introduction i.e. short term focus of energy efficient driving of a single train, medium term applicability of optimised use of regenerative braking using synchronisation and the long-term implementation time scale of flexible headway scheduling to adapt supply and demand. However, these are concentrated on part of the system not the whole and can be understood as measures lacking a valid framework for monitoring.

The combination of different operational phases, the unique driving style of each driver and the effects of train interactions have an immense impact on energy

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[2] http://cometandnova.org/

consumption, capacity availability and service level. Several approaches to cast light on this interplay has been attempted in the literature (D'Ariano and Albrecht, 2006; Albrecht, 2009; Albrecht *et al.*, 2010a; Albrecht *et al.*, 2010b; Chen *et al.*, 2010b; Fan *et al.*, 2012; Lu *et al.*, 2013b; Jaekel and Albrecht, 2014; Zhao *et al.*, 2015).

Despite the importance and relevance of driving style when considering energy usage, there is relatively small amount of experimental data in the academic literature. Kubín and Ferková (2015) reported the evidence they found on the influence of driver style in trams in the Czech Republic. Powell and Palacín (2015a; b) described a benchmarking assessment of driving styles on a mixed traffic urban rail system and its influence on energy consumption. Lukaszewicz (2001) provided a detailed analysis of Swedish freight trains although it considers the braking effort level demanded by the driver rather than the actual deceleration achieved.

Similarly, benchmarking and performance evaluation for urban rail systems using indicators has been reported in the literature, albeit sporadically. This primarily focuses on sub-systems e.g. stations (Casals *et al.*, 2016). Little to no evidence is found in the literature on rail-specific energy performance indicators. Lu *et al.* (2013a) proposed using the concept of quality of service (QoS) as the basis for an evaluation framework. Built on this work and expanding it to a quality of service quantitative evaluation (QoSQE), Nicholson *et al.* (2015) developed a framework for benchmarking and evaluation of rail operations performance defining a number of KPIs as part of their approach. However, while energy is acknowledged as an important contributor and measure to quality of operation, the authors focused instead their framework on other aspects of performance e.g. journey time and punctuality. One single KPI was devoted to the average energy consumed per service for a given origin-destination (O-D) pair. Labelled Energy Consumption KPI (EG KPI), it relates to the average energy consumed for a given O-D service pattern over a specific time. Other studies reported in the literature have concentrated on computer-based simulation investigations on the influence of congestion on delays (Lindfeldt, 2008), traffic control strategies under disturbed conditions (Goverde *et al.*, 2013), varying timetable homogeneity effects on propagation of delays (Vromans *et al.*, 2006), timetable robustness indicators (Jensen *et al.*, 2014). Binder *et al.* (2015) proposed a number of key performance indicators as part of a framework to evaluate the performance of railways under severe disruption although none of these KPIs was related to energy.

2.5. Chapter conclusions

Urban railway systems have characteristics that make them unique e.g. short distance between stations and high frequency of operation. This translates into duty cycles and associated energy consumption patterns over a time-speed profile. The energy usage of rail systems in general and urban ones in particular can broadly be categorised into traction and non-traction consumption. Both AC and DC electrification is used on urban rail systems. Regardless of the type of electrification, railway power supply networks essentially consist of subsystems e.g. traction power distribution systems that are core to the identification of energy flows. A Sankey diagram has been introduced illustrating main flows of power and energy consumption in a typical urban rail system. These flows have been obtained based on the analysis of the breakdown of urban rail energy usage from data published for different European systems. In general, it has been observed that 70–90% of the total energy consumption in urban rail systems is due to rolling stock operation, whereas the rest is used in stations and other infrastructure within the system. Moreover, it has been found that approximately 50% of traction energy may be dissipated during braking phases, which highlights the great energy saving potential offered by the use of regenerative braking. In turn, the auxiliary equipment of the rolling stock (mainly the comfort functions) may account for approximately 20% of its total energy consumption, with significant dependencies on the type of service and climate conditions.

In addition, the literature shows that the majority of recent advances to reduce energy consumption in railway systems have focused on the traction subsystem, primarily by using regenerative braking, applying energy-efficient driving strategies, or improving the propulsion chain efficiency (Powell *et al.*, 2014). This is also in line with the three approaches to energy optimisation in urban rail systems operation proposed by Oettich *et al.* (2004) i.e. driving style and timetable, regenerative braking and adapting supply to demand in a flexible way. A systemic approach to energy usage of urban rail systems is currently lacking.

A review of the literature on energy management systems applied to the industrial sector has shown that there is a clear analogy between industry and public transport systems (and by extension, urban rail systems) concerning the barriers, needs and methods used for energy management. Energy efficiency monitoring and constant analysis of consumption form an important basis for energy management and a critical step to close the energy efficiency gap. Furthermore, there is evidence of the integral part that performance measurement plays in successful energy management. To this extent, the definition and application of appropriate key performance indicators (KPIs) for energy efficiency is paramount. The review of the literature also suggests that the use of thermodynamic and physical-thermodynamic indicators is the most suited for urban rail systems. This affirms the suitability and importance of an effective KPIs system within a framework for monitoring and enhancement of urban rail systems energy performance, conservation and efficiency gap reduction.

Energy efficiency is linked to (sectoral) competitiveness and environmental benefits e.g. GHG emissions. There is no one single unambiguous quantitative measure of energy efficiency. Instead, indicators must be used. Generally speaking, energy efficiency refers to using less energy to produce the same amount of service or useful output. This is of significant relevance to rail/transport systems as it implies that no reduction in the service levels (and consequently competitiveness) can be justified/used to improve the energy efficiency of the system e.g. running fewer trains.

Accounting, performance measurement and benchmarking are three essential aspects of assessing energy performance of systems. The lack of an integrated system-wide energy monitoring framework for urban rail systems is addressed by this thesis, supported by the evidence found in the literature on the development of energy management systems in comparable industrial structures.

Chapter 3-RESEARCH METHODOLOGY

3.1. Research design premise

The review of the literature has shown that despite the impact, significance and growing awareness of energy usage in urban rail systems, the majority of recent advances to reduce energy consumption are concentrating on the vehicle (e.g. traction) and the way it is operated (e.g. traffic aspects). While there is much merit in this body of work, it appears insufficient to address the issue of energy conservation and closing the efficiency gap in a highly complex system given that it tends to use a subsystems approach. There is a need to address these issues from a wider systems perspective. Solutions that concentrate on the parts rather than the whole tend to miss the crucial interactions between those parts, failing to recognise the problem of sub-optimisation i.e optimising the performance of one part or subsystem might have effects elsewhere detrimental for the whole (Jackson, 2003). As discussed in Chapter 1, the purpose of this thesis is to fill this gap in the existing knowledge by supporting a whole systems view of the energy performance of urban rail systems leading to the enhancement of their energy conservation levels. To do so, this research identifies energy flows within the system, proposing a comprehensive hierarchical set of energy related performance indicators and associated methodology as part of an integrated and dynamic monitoring framework. Interventions deploying suitable technologies and strategies, either on their own or in combination can then be assessed to improve the energy conservation and performance prospects of the system.

The evidence found in the literature, as discussed in Chapter 2, shows that while there are not apparent systemic approaches for the monitoring and assessment of energy conservation in urban railways, there is a very interesting parallel between energy management theories for complex industrial settings and those from complex transport systems such as urban railways. This is particularly relevant for the barriers, needs and methods used, in particular the definition and application of appropriate KPIs being at the crux of a framework for energy performance monitoring. The literature discussed in Chapters 1 and 2 has also highlighted a significant emphasis on traction aspects when exploring technologies and strategies to reduce energy usage in rail systems in general and urban ones in particular. Clear approaches have been proposed (e.g. Oettich *et al.*, 2004) suggesting that energy consumption of urban rail systems can be optimised by focusing on driving style and timetable, regenerative braking and adapting service offer to travel demand in a flexible and dynamic way. However, there is a lack of knowledge related to the assessment of the combine effects of these approaches, the existing energy flows in the system and the influence of them resulting from multiple interventions and a flexible methodology measuring such influence in a quantifiable and systemic manner.

Based on the gaps in the literature identified, this thesis pursues the following research objectives and associated research questions (see also Table 1, p. 9):

Research Objectives:

- To explore how energy is used in urban railway systems;
- To develop a holistic monitoring framework for energy optimisation of urban railway systems;

Research Questions:

- Which are the key energy flows influencing consumption at system, sub-system and component levels?
- Are current approaches to energy efficiency and monitoring suitable for system-wide optimisation?
- Could an adaptable multi-level monitoring framework provide a realistic systems perspective on energy performance of urban railways?

The research presented in this thesis has adopted a pragmatic perspective, incorporating both deductive and inductive approaches gathering information about interdependencies, sequences and data to build framework components, framework execution and iteration procedures and inductive methodological approaches constituting the main thrust of the research (e.g. systematic literature review, dynamic framework development, expert consultations for validation, and case studies for illustration).

This chapter discusses the research philosophy that frames the thesis as well as the associated approach underpinning the choice of methodology applied.

3.2. Research philosophy

Framing a research endeavour within a particular philosophical worldview is an essential step for any successful study. A worldview (Wittgenstein, 1922) can be interpreted as “a basic set of beliefs that guide action” (Guba, 1990). As indicated by Creswell (2013), the concept has also been termed epistemology and ontology and perhaps the more widely used, paradigm. Guba (1990) characterised paradigms based on how they address ontological, epistemological and methodological questions i.e. what is reality? How do we know something? How to find out? Methodological questions are also known in the literature as axiology

(Denzin and Lincoln, 1994) and praxiology (Mingers and Brocklesby, 1997). Mangan *et al.* (2004) highlighted the central role of a paradigm to the research process. The authors described it as “a very general conception of the nature of scientific endeavour within which a given enquiry is undertaken”. Cibangu (2010) stated that “paradigms undergird the way researchers design their actions or decisions in general and research in particular”. The concept of a paradigm was firmly engrained in research philosophy by the influential work of Thomas Kuhn (1962) who, prompted by the difference in discourse about scientific problems and methods in the social and natural sciences, described paradigms as “[…] universally recognised scientific achievements that for a time provide model problems and solutions to a community of practitioners”.

There is a fertile and rich literature covering the philosophical foundations of research. Tentatively and broadly speaking, a taxonomy of worldviews could result in two main distinctive schools: positivism and constructivism. Many other terms are used to refer to these e.g. positivism is related to post-positivism and empirical science (Creswell, 2013) while constructivism is often related to social constructivism (Creswell, 2013), interpretivism (Teddlie and Tashakkori, 2009; Easterby-Smith *et al.*, 2012; Bryman, 2015), historicism (Teddlie and Tashakkori, 2009) and phenomenalism (Bryman, 2015). In broad terms positivism/post-positivism “hold a deterministic philosophy in which causes (probably) determine effects” (Creswell, 2013). Bryman (2015) stressed that “positivism entails elements of both deductive approach and inductive strategy”. Mangan *et al.* (2004) argued that while positivism has been the paradigm that has dominated physical science, it has been losing relevance within the social science community, adopting instead a worldview of paradigm aligned with the ideas of phenomenalism or constructivism, which in effect are opposed to positivism. This is supported by Bryman (2015) describing interpretivism as “a term that usually denotes an alternative to positivism orthodoxy”. Table 7 below summarises these basic belief systems.

Fundamental questions forming the basic belief system	Paradigm	
	Positivism	Constructivism
Ontological	**Realist**	**Relativist**
What is reality?	Reality exists governed by undeniable natural laws and mechanisms	More than one reality exist based on the context of the observer/researcher
Epistemological	**Dualist, objectivist**	**Subjectivist**
How do we know something?	The observer/researcher adopts a neutral, non-interactive approach	The observer/research and the subject are interactive influencing the findings
Methodological	**Experimental**	**Hermeneutic, dialectic**
How to find out?	Questions and hypotheses are proposed prior to subjecting them to empirical testing	Meaning and findings are obtained though interpretation and human interaction

Table 7. Contrasting characterisation of positivism and constructivism paradigms. Adapted from (Guba, 1990; Creswell, 2013; Bryman, 2015)

There is an increasing acceptance that the quest for knowledge is not always framed within these two opposing paradigms but somewhere along the continuum that connects them (Tashakkori and Teddlie, 1998; Easterby-Smith *et al.*, 2012). Figure 10 represents such a paradigmatic continuum. This has profound relevance for the emergence of pragmatism and the use of triangulation as a valid research method for disciplines requiring the use of multiple principles e.g. transport applies engineering, economic, social and legal principles.

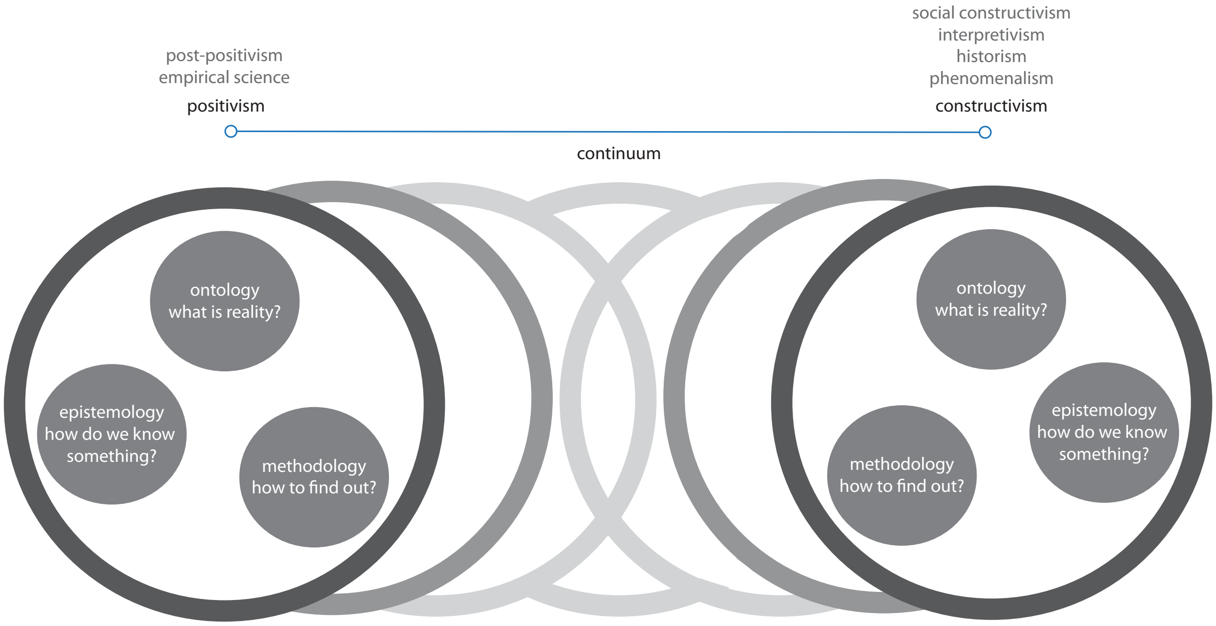

Figure 10. Paradigmatic continuum

Pragmatism is a third and perhaps more relevant worldview or paradigm to this research. It is not a mere blend of both opposing paradigms but as Guba (1990) argued citing Kloppenberg (1986)

> *"The philosophers of the* via media *carefully avoided fruitless attempts to reconcile the irreconcilable; they tried instead to jostle philosophy into a productive confrontation with doubt"*

Pragmatism is a worldview emerging from actions, situations and consequences rather than existing or antecedent conditions (positivism); the concern is on what works and solutions to problems (Creswell, 2013). Although pragmatism as a research approach was first considered in the mid 1850s, Tashakkori and Teddlie (2010) identified the early 1990s as the advent of "pragmatism and the compatibility thesis[3]" cementing mixed methodology and the work of Howe (1988) who suggested the use of a different paradigm i.e. pragmatism. Tashakkori and Teddlie (1998) stated that pragmatism and the pragmatist researcher "consider the research question to be more important than either the method they use or the paradigm that underlies the method" advising the reader:

> *"Study what interests and is of value to you, study it in the different ways that you deem appropriate, and utilise the results in ways that can bring about positive consequences within your value system."*

They went on referring to this approach as "the dictatorship of the research question". Given that the research described in this thesis is to address a research problem (how to improve energy conservation in urban rail systems) rather than the researcher's perspective on the topic, pragmatism and its research methodological approach are considered the paradigmatic root of this thesis. Furthermore, addressing research questions related to applied subject areas (e.g. transport, supply chain management) requires a systems view that is holistic in nature by constructing a breath of perceptions arising from understanding the research problem through different philosophical standings, avoiding the shortcomings of adopting extreme paradigmatic positions i.e. positivism or constructivism (Sweeney, 2013)

3.3. Research methodology considerations

The term *method* tends to be used in a variety of contexts and with multiple meanings that lead to confusion e.g. it is used to refer to methodologies as well as techniques. Mingers and Brocklesby (1997) discussed this issue providing a definition of what a paradigm, methodology, technique and tool are. The following diagram (Figure 11) summarises them.

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[3] Up to then, the incompatibility thesis was dominant, stating that compatibility between quantitative and qualitative methods is impossible due to the incompatibility of the paradigms that underlie the methods.

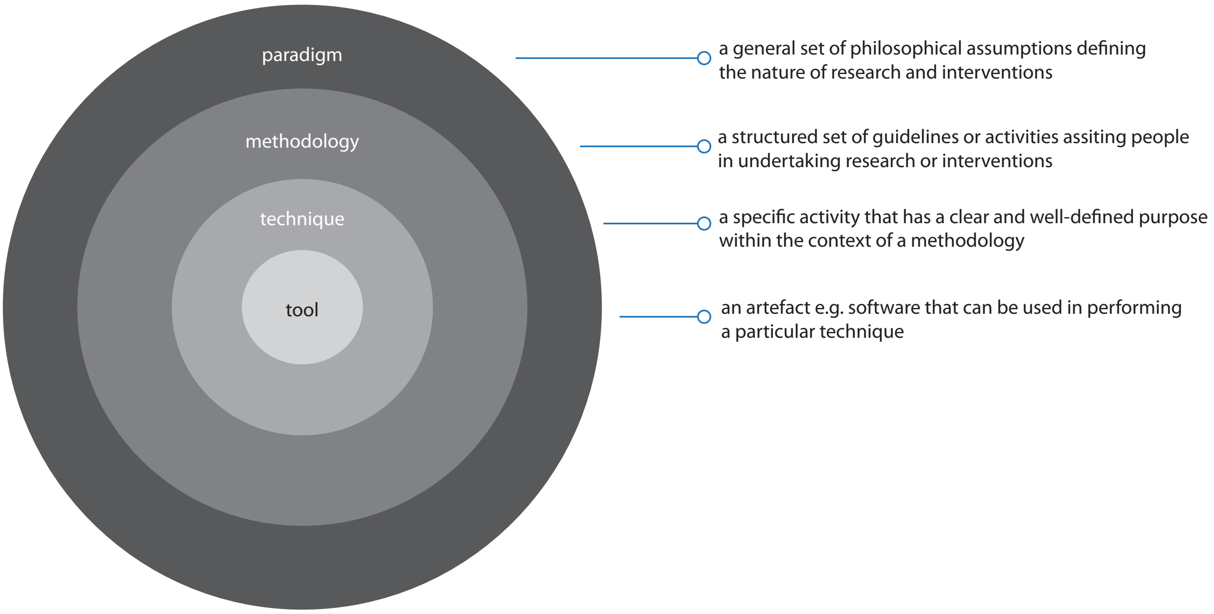

Figure 11. Terminology definitions and hierarchy adapted from (Mingers and Brocklesby, 1997)

This hierarchical proposition constitutes the basic structure whereupon to define research undertakings. It illustrates the relationship between methodology and techniques as the *what* and the *how* i.e. what type of research activities need to be done (methodology) and in which particular ways these activities can be performed (techniques). The overarching philosophical dimension of the research (paradigm) provides the *why* for the methodology (Mingers and Brocklesby, 1997). This distinction between methodologies and techniques is further clarified in Mingers and Gill (1997) indicating that the latter is “a set of prescribed procedures that lead to an end point without the need for reflective intervention” whereas a methodology “embeds a set of techniques and tools within a larger process involving judgment”. Evolving from these definitions and principles, the concept of multi-methodology emerges. At a fundamental level, it can be understood as the approach of combining whole methodologies, or parts of, within a particular intervention (Mingers and Brocklesby, 1997; Mingers and Gill, 1997). Such combined methodologies can come from a single philosophical origin or from various thus enabling the application of multi-paradigm multi-methodological approaches.

The use of multiple methodologies within a given research programme and the steering away from “pragmatic isolation” (Mingers and Brocklesby, 1997) has also been covered in the literature advocating ‘triangulation”. Tashakkori and Teddlie (2010) credited Denzin (1978) with introducing the term “triangulation” which included using several data sources (“data triangulation”) and multiple methodologies (“method triangulation”). Mangan *et al.* (2004) cited Easterby-Smith *et al.* (1991) who identified four types of triangulation i.e. data (multiple sources), investigators (more than one collects data), methodological (qualitative and quantitative) and triangulation of theories where “a theory is taken from one discipline and used to explain a phenomenon in another discipline". Although still the subject of philosophical debate (e.g. Tashakkori and Teddlie, 2010), the assertion by Howe (1988) that quantitative and qualitative methodologies are compatible and can be mixed based on the principles of pragmatism suggests that this approach is fitting for the purpose of this thesis.

The philosophical underpinning of research influences the choice of methodology as it does the theoretical drive of the research endeavour. Morse (1991; 2003) defined this theoretical drive as "the overall thrust" which can be "inductive (for discovery e.g. what is going on? What is happening?) or deductive (for testing e.g. a hypothesis or how much? How many?)" Linking these inductive and deductive theoretical drives to qualitative and quantitative research approaches respectively. Figure 12 summarises the spectrum of (non-exhaustive) qualitative and quantitative methodologies along the paradigmatic continuum.

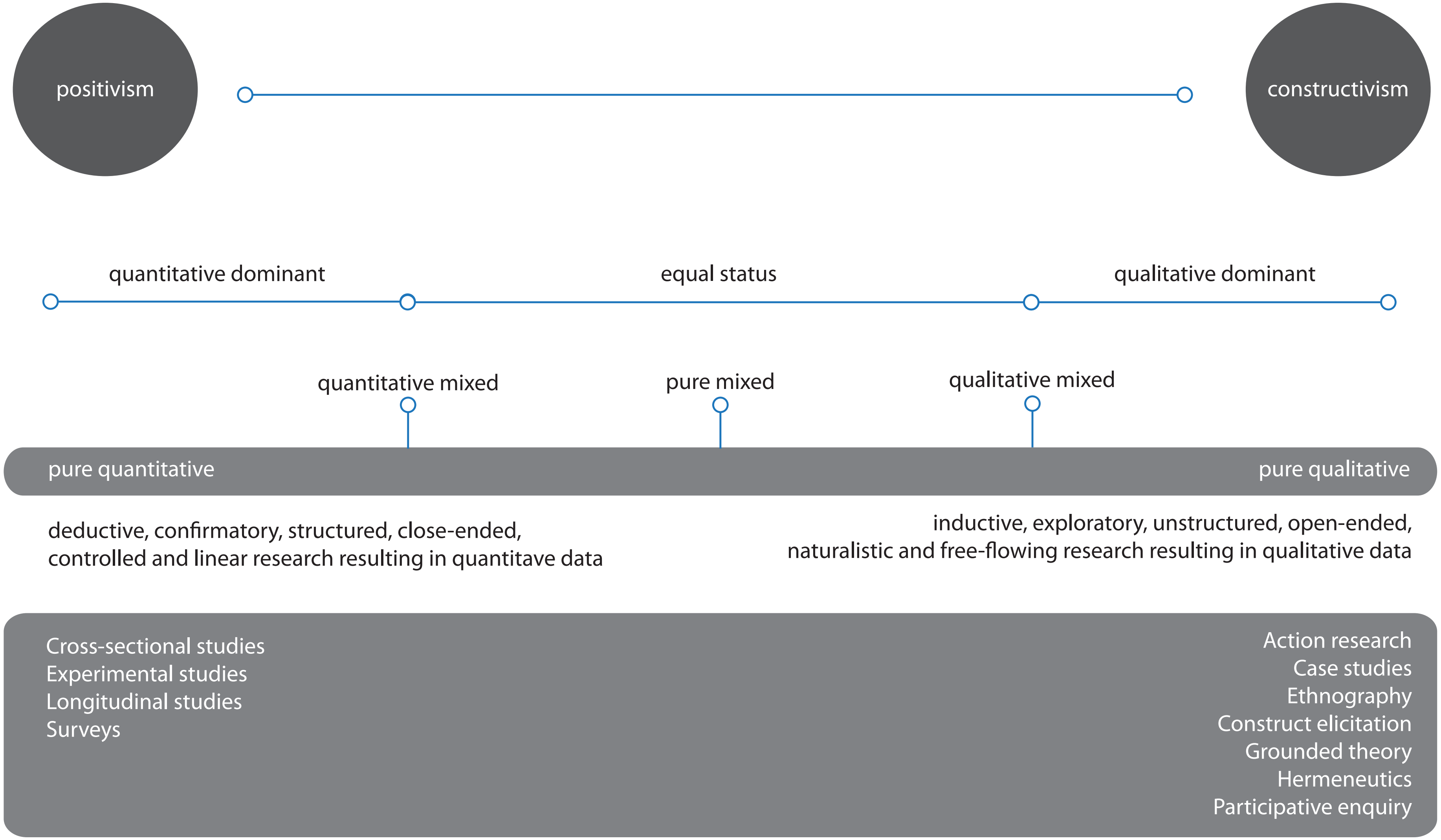

Figure 12. Qualitative and quantitative methodologies and their paradigmatic grounding adapted from (Collis and Hussey, 1997; Johnson and Turner, 2003; Johnson *et al.*, 2007)

Tashakkori and Teddlie (1998; 2010) highlighted the importance of identifying the appropriate stage of integration i.e. the combination of methods within a given stage of inquiry. Specifically, they identified four stages i.e. (1) within the research questions, (2) within data collection, (3) within data analysis, (4) during interpretation. Furthermore, Creswell *et al.* (2003) suggested six major designs for mixed research based on four aspects criteria i.e. implementation, priority, integration and theoretical perspective, the latter also known as transformative design. The following table (Table 8) summarises the types of research design based on these four criteria.

Design type	Implementation	Priority	Stage of integration	Theoretical perspective
Sequential explanatory	Quantitative then qualitative	Quantitative	(4)	Possible
Sequential exploratory	Qualitative then quantitative	Qualitative	(4)	Possible
Sequential transformative	Either	Quantitative, qualitative or equal	(4)	Present
Concurrent triangulation	Concurrent collection of quantitative and qualitative data	Equal	(3) or (4)	Possible
Concurrent nested	Concurrent collection of quantitative and qualitative data	Either	(3)	Possible
Concurrent transformative	Concurrent collection of quantitative and qualitative data	Quantitative, qualitative or equal	(3)	Present

Table 8. Types of mixed methods designs modified from Creswell *et al.* (2003)

Based on the previous considerations discussed in this section 3.3, the research presented in this thesis has an inductive theoretical thrust (e.g. how is energy being used in urban rail systems) while containing some deductive aspects (e.g. monitoring framework execution) suggesting that a sequential exploratory approach dominated by primarily qualitative methods would be the most suitable.

3.4. Research framework

As indicated in section 3.1 the assessment of the literature has shown that despite the impact, significance and growing awareness of energy usage in urban rail systems, the majority of recent advances to reduce and optimise energy consumption are concentrating on the rolling stock (e.g. traction consumption) and the way it is operated (e.g. traffic aspects). The unquestionable merit and relevance of this body of work does not diminish its limitations when addressing the issue of energy conservation and closing the efficiency gap in a highly complex system. This is predominantly due to the given tendency found in the literature to use a subsystems approach. There is a need to address these issues from a systems perspective.

Solutions that concentrate on the parts rather than the whole tend to miss the crucial interactions between those parts, failing to recognise the problem of sub-optimisation i.e optimising the performance of one part or subsystem might have effects elsewhere detrimental for the whole (Jackson, 2003). This is also captured by Reynolds and Holwell (2010) who identify the two deceptions of non-systems thinking as “avoiding the inevitable interconnectivity between variables”, which is linked to reductionism and “working on the basis of a single unquestioning perspective”, which is linked to dogmatism. This in turn is related to two transitions in the history of systems thinking identified by (Bawden, 1999; 2010) towards holism and pluralism countering reductionism and dogmatism respectively, with holism being at the crux of it. Holism considers systems to be more than the sum of their parts (Checkland, 1981; Jackson, 2000; 2003).

Systems thinking is a “framework of thought that allows us to deal with complex things in a holistic way” (Flood and Carson, 2013). The origins of systems thinking can be traced back to ancient civilisations (Checkland, 2000; Jackson, 2003; Reynolds and Holwell, 2010). The seminal work of (Von Bertalanffy, 1950; 1968) suggesting the trans-disciplinarity of open systems from a biology context into other domains translated into a “general systems theory” founding effectively modern systems thinking (Jackson, 2003). Similarly influential was the work of Wiener (1948) who introduced *cybernetics,* the science of control and communication as key components governing processes in systems. In his assessment of Wiener’s work Jackson (2003) highlighted as one of Wiener’s main contributions introducing the concept of negative feedback (denoted “-” in system dynamics diagrams) whereby information is transmitted about behavioural divergence from goal leading to corrective measures being taken to restore behaviour towards the goal, as depicted in Figure 13.

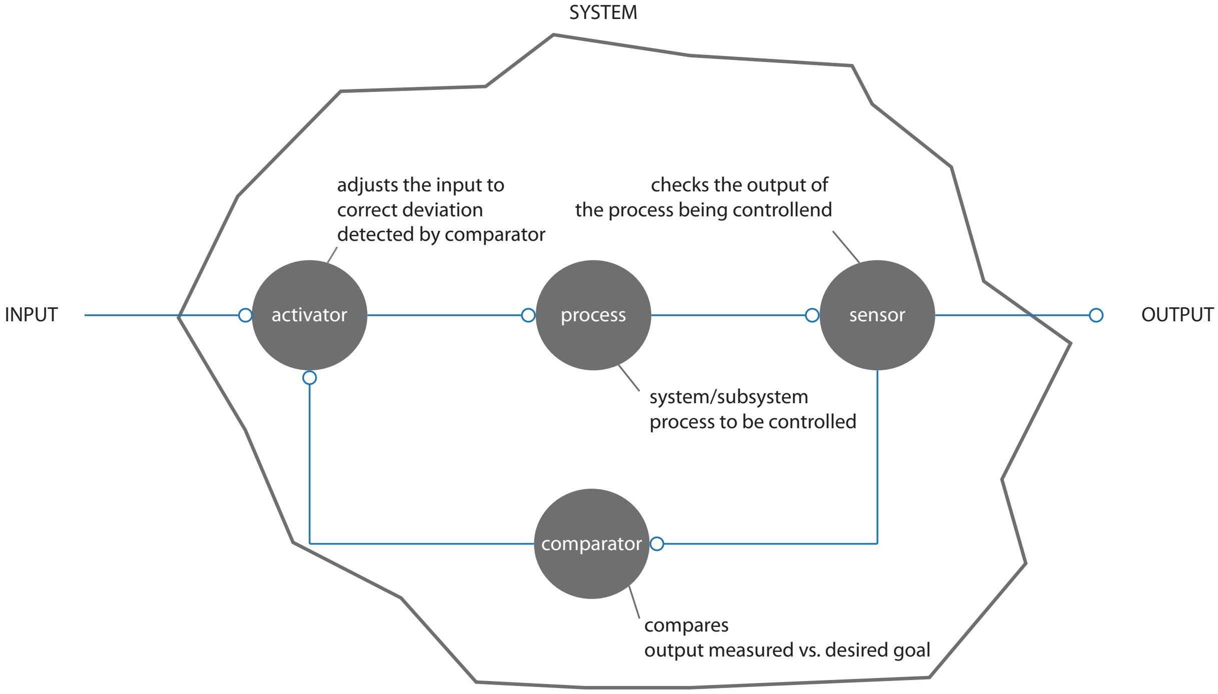

Figure 13. Wiener's negative feedback system adapted from (Jackson, 2003)

Jackson went on to complete this assessment of Wiener's contribution by suggesting that systems thinking also requires positive feedback (denoted "+" in systems dynamics diagrams) which rather than neutralising deviations from goals, it amplifies them. The use of feedback loops is particularly relevant in techniques (e.g. "signed digraph" and "causal loop") associated with the system dynamics approach and methodology. Systems dynamics was developed by Forrester (1958) at the Massachusetts Institute of Technology (MIT) in the 1950s. In Jackson's account of Forrester's seminal theory (Jackson, 2003) he described that according to it, the multiple variables of complex systems become causally connected through feedback loops in a systemic interrelationship, effectively creating the structure of the system which in turn is the factor of system behaviour. Forrester (1969) explored a number of applications for his theory including urban systems. He explained his approach through the fundamental differences between simple and complex systems. Simple systems have intuitive first-order responses associated with negative feedback loops. In this context, cause and effect are closely related in time and space. In complex systems on the other hand, cause and effect are not that closely related in either time or space. Instead, they have a "multiplicity of interacting feedback loops". Complex systems are of high order usually containing positive as well as negative feedback loops. A methodology applying this theory followed Forrester (1961; 1971). System dynamics was promoted as the fifth discipline by Senge in the influential book with the same title (Senge, 1990).

In addition to this, during the second half of the twentieth century new engineering techniques were developed to deal with new complexities and focusing on the complex whole rather than the individual components becoming a discipline in its own right termed systems engineering (Gorod *et al.*, 2008). This was part of a number of systems methodologies that emerged during that period which included operational research (OR) and systems analysis (SA) in addition to systems engineering (SE), all of which have been labelled as “hard systems thinking” (Jackson, 2003; Reynolds and Holwell, 2010). There is a rich literature providing a taxonomic overview of systems thinking. According to Reynolds and Holwell (2010) the most widely used classification of systems approaches distinguishes them into “hard”, “soft” and “critical”. The work of Checkland (e.g. Checkland, 1981; 2000) is credited with the questioning of a “hard” approach to systems thinking in favour of a “soft” assumption whereby systems are “epistemological constructs rather than real world entities” (Reynolds and Holwell, 2010). Other authors, notably Ulrich (1983) and Jackson (1990), developed a third strand (“critical”) in systems thinking to deal with the inadequacies of both “hard” and “soft” systems. Table 9 provides an overview of the main methodologies associated with these three categories.

Systems category	Key approach/methodology
Hard systems	General systems theory; Classical (first order) cybernetics; Operations research (OR); Systems engineering (SE); Socio-technical systems; RAND-systems analysis (SA); System dynamics
Soft systems	Inquiring systems design; Second order cybernetics; Soft systems methodology; Cognitive mapping for strategic options development and analysis
Critical systems	Critical systems heuristics; System of systems methodologies; Liberating systems theory; Interpretative systemology; Total systems intervention; Systemic intervention

Table 9. Overview of selected approaches for hard, soft and critical systems adapted from Reynolds and Holwell (2010)

Alternative classifications have been created based on the situations encountered by systems i.e. a simple/complex dimension related to interdependencies and a unitary/pluralist/coercive dimension related to engagement with multiple perspectives (Jackson, 2003). This approach evolved into what is called systems of systems (SoS) and systems of systems methodology (SoSM) which as been championed primarily in management applications by Jackson but which has been also postulated for other areas such as transport e.g. the U.S. National Transportation System (NTS) (DeLaurentis and Callaway, 2004; Delaurentis, 2008). Systems of Systems Engineering (S2 Engineering) was defined by Eisner *et al.* (1991) in response to the increasing complexity of systems. S2 Engineering was conceived as a meta-systems engineering framework with three main categories i.e. integration engineering, integration management and transition engineering, each under a nominal set of engineering processes. It proposes that the optimisation of the overall system of systems cannot be achieved through optimisation of each of the individual systems. Systems of systems can be framed within the critical systems category and while not rooted in pure pragmatism, the methodological pluralism that critical systems thinkers pursue can be considered aligned with pragmatism in the sense of their "common concern with developing a flexible and responsive practice of intervention" (Midgley, 1997).

Further classifications include Jackson (2003) who discerned four types of system approaches depending on whether their aim is improving goal seeking and viability (type A), exploring purposes (type B), ensuring fairness (type C) or promoting diversity (type D). Particularly relevant is that the overarching measure of success for type A systems is efficiency (are the minimum resources used in goal seeking?) and efficacy (do the means used enable realisation of goals?). Similarly, type D postmodern systems evaluate their success on the basis of exception (what otherwise marginalised viewpoints have been brought to the fore?) and emotion (do actions being proposed feel appropriate at local circumstance level?).

The contextual nature of the research problem targeted in this thesis is that of complex systems. To address it, the thesis has adopted a pragmatic perspective incorporating deductive gathering of information about interdependencies, sequences and data to build framework components, framework execution and iteration procedures (RO_02, RQ_03)[4] as well as incorporating inductive methodological approaches and associated techniques that constitute the main thrust of the research (e.g. systematic literature review, dynamic framework development, expert consultation for validation, case study for illustration). This inductive thrust is adopted to infer a holistic view of energy usage in urban rail systems (RO_01, RQ_01) and to define a comprehensive methodology to aid implementation of interventions aiming at reducing the energy efficiency gap to enhance the level of energy conservation in any given urban rail system (RO_02, RQ_02). Figure 14 provides a graphical representation of the selected research framework.

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[4] Research objectives (RO_) and Research Questions (RQ_), see Chapter 1

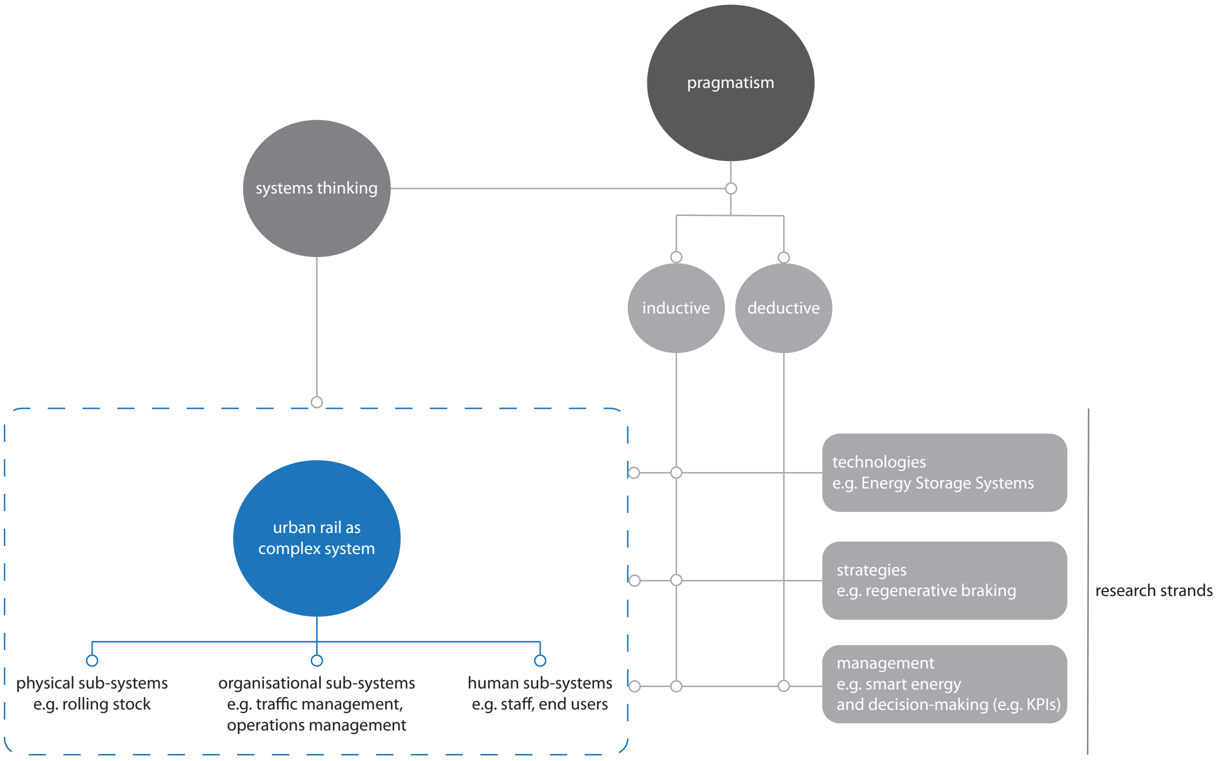

Figure 14. Theoretical research framework selected

3.5. Research design: Methodology and techniques structure

This research is underpinned by a pragmatist worldview incorporating inductive and deductive methodologies using a systems thinking and holistic approach to address the research objectives (ROs) and questions (RQs) formulated in sections 1.3.1 and 3.1. Methodologically, following the doctrine of pragmatism, it borrows from a number of methodologies and techniques to fulfil its aim. Specifically, it uses an adapted systems analysis methodology (Figure 15) typical of hard systems positions (type A).

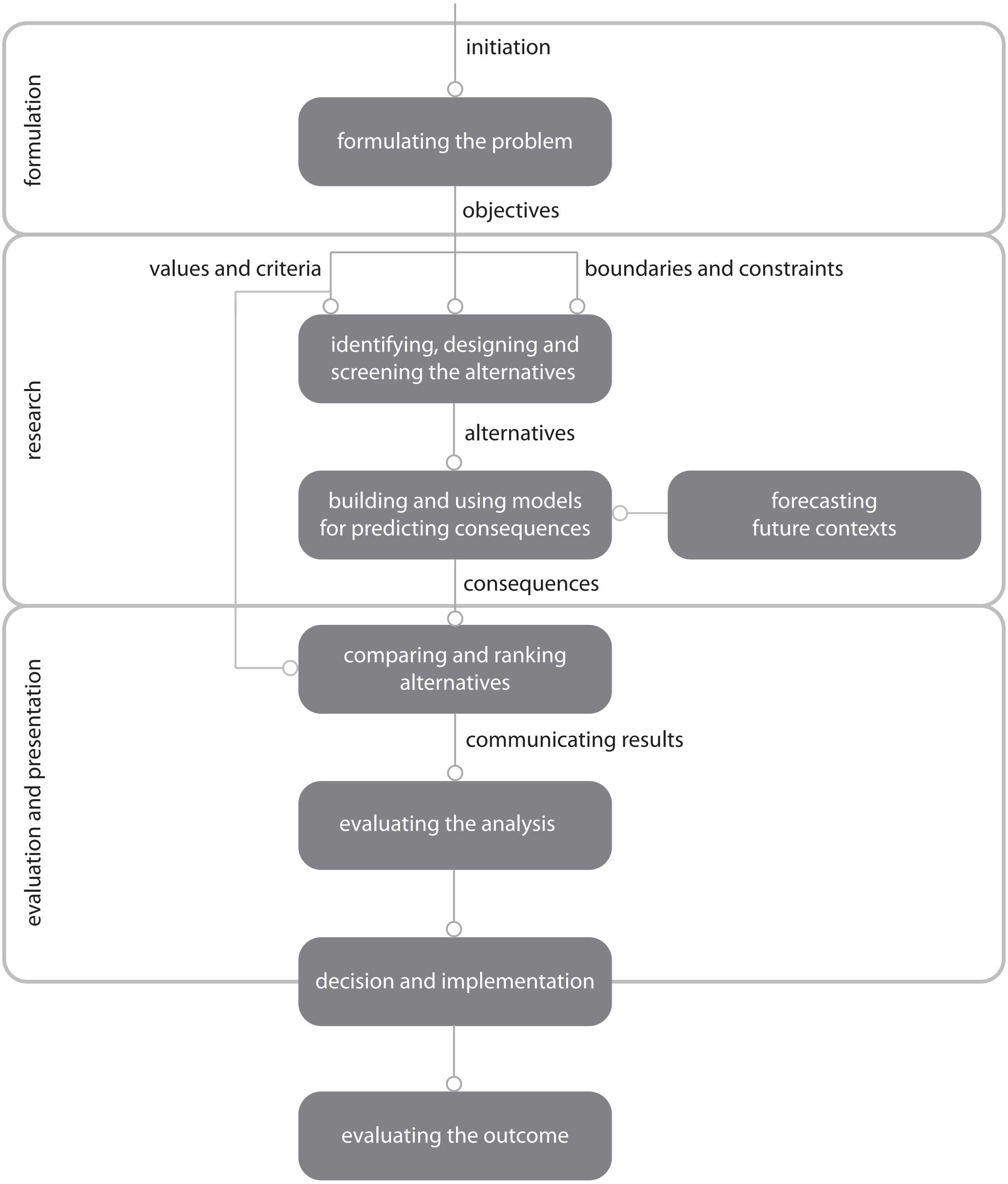

Figure 15. The systems analysis methodology adapted from Miser and Quade (1988)

The essential starting premise of systems analysis is the identification of the existence of a problem by someone involved with a socio-technical system (Miser and Quade, 1985; 1988; Miser, 1995). Socio-technical systems according to Geels (2004) consist of “artefacts, knowledge, capital, labour, cultural meaning, etc.”. A more detailed definition based on Geels is given by Schwanen (2015) who describes a socio-technical regime as

> *"A set of rules—cognitive routines, shared beliefs, social norms and conventions, regulations, industry standards, protocols, contracts, laws and so forth—that fulfill a societal function (e.g., everyday mobility) and thereby condition the practices through which the technology, infrastructure, markets, cultural values, user practices, maintenance and repair, regulation and formal knowledge that make up socio-technical systems are reproduced"*

Railways in general and urban rail systems in particular are socio-technical systems. Wilson *et al.* (2007) described railways as "large, complex distributed socio-technical systems". The authors went on to provide a comprehensive account of the reasons behind this assertion arguing that railways meet the classic criteria for socio-technical systems given that

> *"It is a purposeful system that is open to influences from, and in turn influences, the environment (technical, social, economic, demographic, political, legal, etc.); the people within it must collaborate to make it work properly; and success in implementation of change and in its operation depends upon as near as possible jointly optimizing its technical, social, and economic factors."*

The authors added that railways are an "excellent example of a modern complex socio-technical system" (Wilson *et al*., 2007). This key characteristic of being a socio-technical system with a complexity dimension suggests the suitability of using a systems analysis methodology as part of the research design. This approach is adapted to elaborate an energy efficiency implementation methodology for urban rail systems which includes the use of a holistic set of key performance indicators designed to account for the interdependencies of each component and sub-system of any given urban railway system.

The research also adopts judgemental and conceptual models (Jackson, 2003) used to gather the views of individuals seeking to reinforce the construction of robust feedback loops as part of the methodology reflecting expert group views. This is further explored by using techniques such as structured interviews which has been found to be effective for quantifying judgmental uncertainty (Merkhofer, 1987).

Figure 4 (Section 1.3.2, p. 10) illustrates the structure of this thesis and how the different research objectives, research questions and contributing chapters are grouped into three research phases, each of which is related to the three research strands in Figure 14. The methodological structure for these three phases is illustrated in Figure 16.

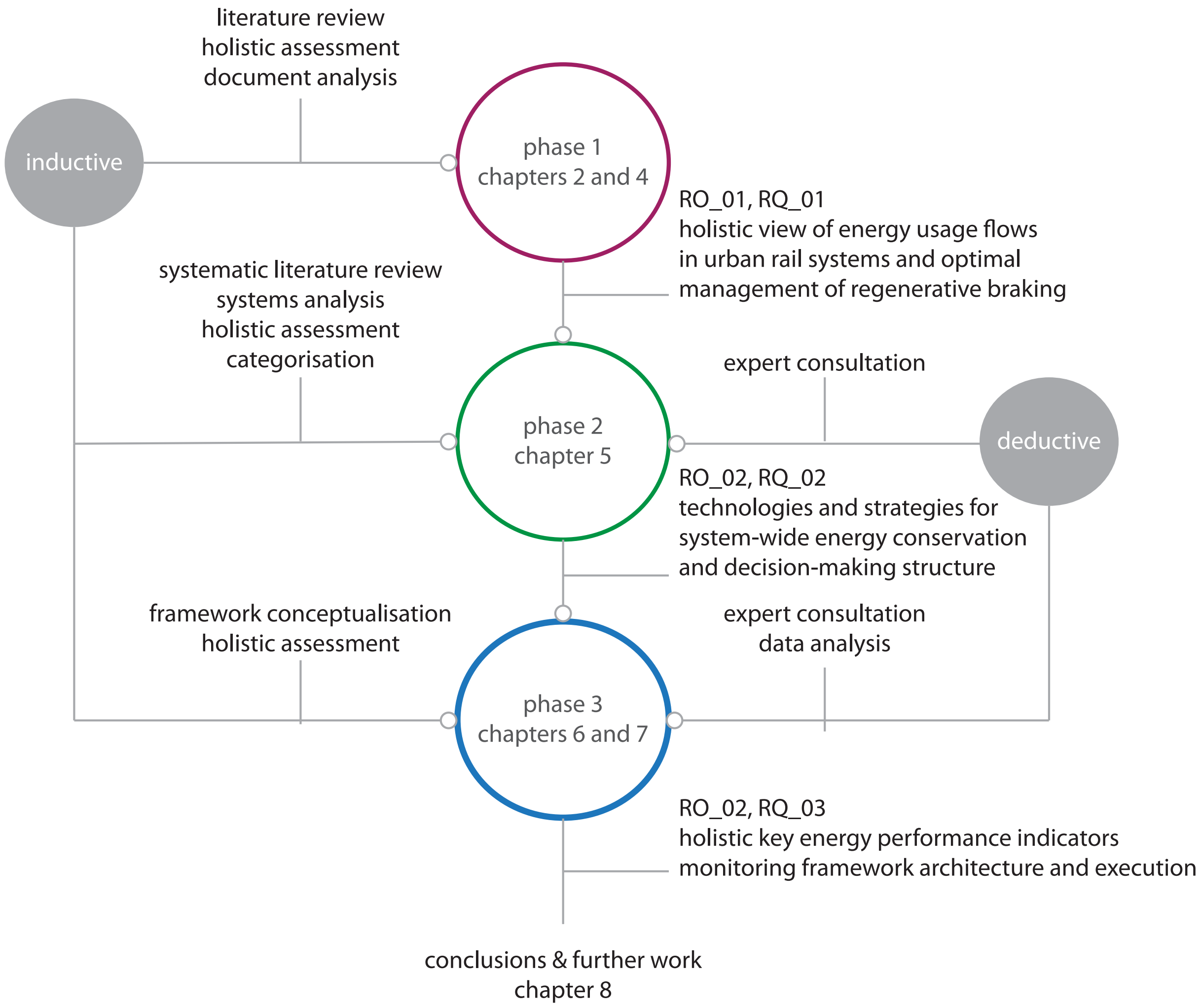

Figure 16. Three-phased methodological triangulation and expected outcomes

Phase 1 uses an inductive approach applying qualitative techniques to address the research objective 01 and its associated research question 01. Specifically, a systemic review of the literature is conducted to explore the use of energy in urban rail systems identifying the essential flows influencing critical consumption patterns affecting system-wide energy conservation, performance and gap efficiency reduction.

Phase 2 addresses research question 02 having also an inductive nature as it enquiries about the suitability of current practice applying document and data analysis, cross-study and systemic review to enquiry about the suitability of existing interventions using technologies and/or strategies to achieve system-wide energy conservation. In addition, it adopts a systems analysis methodology adapted to allow decision-making and monitoring for implementing such interventions.

Phase 3 combines inductive and deductive methodological aspects to develop a holistic and hierarchical framework architecture and its operationalised structure. Techniques used in this phase involve expert consultation and use of data from five urban rail systems to provide an illustrative application.

The adoption of this three-phased methodological triangulation approach facilitates the research described in this thesis. This has produced as its main outcome the definition and validation of a framework architecture for holistic and hierarchical assessment and monitoring of energy performance of urban rail systems and its operationalised version leading to energy conservation and efficiency gap reduction.

3.6. Chapter conclusions

This chapter has discussed the research philosophy framing this thesis, the methodological considerations associated with it and the justification for choosing them.

The research has adopted a three-phased methodological triangulation approach that is rooted in pragmatism and adopting an inductive thrust grounded in systems thinking incorporating methodologies and techniques that are both inductive and deductive in nature. The following Chapters 4 to 7 implement this research framework.

Chapter 4- STRATEGIES AND TECHNOLOGIES FOR MANAGEMENT OF REGENERATIVE BRAKING

4.1. Introduction

The literature review and systemic analysis carried out in Chapter 2 has given a holistic overview of the energy flows identified in urban rail systems, which can be broadly classified into those dedicated to traction and non-traction purposes. While it is simply not possible to provide general figures of the split of usage between these two categories and their sub-systems and components, it is widely accepted that traction purposes tend to have the largest share. In that chapter the example of London was given where an estimated 80:20 ratio split between traction and non-traction consumption has been reported (Figure 9, p. 22). Additionally, the assessment of the traction-destined energy flows has concluded that the braking process produces the largest portion of energy losses as shown in the illustrative Sankey diagram provided (Figure 8, p. 20). Addressing the inefficiency of this latter process, regenerative braking is regarded as one of the most promising solutions to optimising energy usage in electrified urban transport networks. Using an extensive literature review, document analysis and holistic assessment (see Chapter 3 for methodological details), this Chapter 4 investigates the merits of regenerative braking as a core area for improving energy efficiency, comprehensively examining strategies and technologies for its optimal management and deployment. Specifically, section 4.2 provides a detailed description of the fundamentals associated with regenerative braking and the different strategies that can be used for its deployment. Section 4.3 discusses the merits of energy storage systems (ESSs) and the characteristics of various technologies assessing their performance from a techno-economic perspective i.e. the suitability of such technologies from a technical maturity, durability and commercial viability perspective as part of interventions in urban rail systems. Section 4.4 describes the outcomes of the assessment carried out analysing the advantages and drawbacks to categorise the most suitable energy storage systems into their potential deployment conditions i.e. on-board vehicles or stationary (also know as wayside) underlining also key aspects to be considered in the design stages. Section 4.5 explores reversible substations as a complementary technology that could enhance the benefits introduced by energy storage systems and their deployment strategies. Finally, section 4.6 provides a discussion of the main conclusions and findings of this chapter.

4.2. Regenerative braking: Concept and strategies for deployment

4.2.1.Basic considerations

The conversion of kinetic energy into electricity, commonly known as dynamic braking, is based on the capacity of electric motors to also act as generators. The use of this kind of braking is widely used in railway applications as, in contrast to friction braking, it does not generate wear and tear, dust, smell, heat or sound (Vuchic, 2007). A typical electric motor or machine has two basic working modes; i) motoring occurs when both the rotating speed of the motor and the torque are in the same direction and ii) regenerative mode which takes place when these two speeds are in opposite directions (Lu *et al.*, 2014). A rail vehicle torque reduces the speed of the motor during the regenerative mode, generating electric power and hence acting as a generator. In dynamic braking conditions, the regenerated electricity may either be dissipated in banks of variable resistors (known as rheostatic braking) turning it into heat or may be reused within the transport network itself (regenerative braking). Before the outstanding development of power electronics in the last few decades, rheostatic braking was the only available option. Modern controllers and circuitry allow for simple and stable regenerative braking (Schmid and Goodman, 2014) making this technique a very promising approach to reduce energy consumption in electrified urban transport networks. Complementary to this is the added benefit of urban networks, characterised by numerous and frequent phases of acceleration and deceleration, which in turn favours a high rate of braking energy recuperation (see Chapter 2 for more details on operational phases e.g. Figure 4).

4.3. Strategies for deployment of regenerative braking

Typically in regenerative braking, the recovered energy is primarily used to supply the auxiliary and comfort functions of the vehicle itself. Then, the energy surplus may be returned into the power supply line for use of other vehicles within the same network. However, DC distribution networks, which are the most commonly used in urban rail systems, are not always receptive i.e. they are not always able to admit the recovered braking energy. The recovered excess energy can only be sent back to the supply network when a simultaneous consumption takes place, for instance when another train is accelerating in the same electric section. To dissipate the regenerated energy that cannot be used within the system, vehicles are typically equipped with on-board resistors. The use of such resistors has a number of drawbacks, particularly additional weight and costs, but also a potential risk of fire.

The use of ESSs and the improvement of network receptivity are two distinct and significant approaches identified for maximising the use of the recovered energy following an exhaustive review of the literature, as described below.

Equipping rolling stock with energy storage systems facilitates the temporarily accumulation of excess regenerated energy so it can be released in the next acceleration phase (Henning *et al.*, 2005; Lhomme *et al.*, 2005; Destraz *et al.*, 2007; Steiner *et al.*, 2007; Barrero *et al.*, 2008; Chymera *et al.*, 2008; Meinert, 2009; Mir *et al.*, 2009; Miyatake and Matsuda, 2009; Allègre *et al.*, 2010; Barrero *et al.*, 2010; Iannuzzi and Tricoli, 2010; Moskowitz and Cohuau, 2010; Ogasa, 2010; Domínguez *et al.*, 2011a; Iannuzzi and Tricoli, 2011; Jeong *et al.*, 2011; Ciccarelli *et al.*, 2012; Iannuzzi and Tricoli, 2012).

Improving the receptivity of the urban rail power distribution network implies introducing additional loads in the system demanding energy at the same time as the braking process takes place. To achieve this, studies found in the literature suggest that optimising the scheduled timetables so the acceleration and deceleration of trains is synchronised whenever possible (Albrecht, 2004; Chen *et al.*, 2005; Nasri *et al.*, 2010; Boizumeau *et al.*, 2011; Peña-Alcaraz *et al.*, 2011). Additionally, the installation of storage devices in substations or along the track in the form of stationary or wayside ESSs could absorb the surplus regenerated energy, delivering it when required for other vehicles' acceleration (Richardson, 2002; Konishi *et al.*, 2004; Rufer *et al.*, 2004; Brenna *et al.*, 2007; Morita *et al.*, 2008; Battistelli *et al.*, 2009; Barrero *et al.*, 2010; Konishi *et al.*, 2010; Battistelli *et al.*, 2011; Garcia-Tabares *et al.*, 2011; Lee *et al.*, 2011b; Ogura *et al.*, 2011; Iannuzzi *et al.*, 2012a; Iannuzzi *et al.*, 2012b; Teymourfar *et al.*, 2012; Iannuzzi *et al.*, 2013). A further alternative to improve the receptivity of the network is to install DC/AC inverters in substations, which effectively makes them reversible or active substations. This approach allows the regenerated energy to be fed back to the medium voltage distribution network, which is naturally receptive (Mellitt *et al.*, 1984; Gelman, 2009; Cornic, 2011; Ortega and Ibaiondo, 2011b; Warin *et al.*, 2011).

The topographic characteristics of any given urban rail system e.g. track gradients have a significant and notable influence on the amount of energy that can be recovered through braking as it influences the operational behaviour reflected in the timetable. Nevertheless, a number of studies in the literature have quantified the potential savings that regenerative braking could introduce. According to these, the application of regenerative braking in urban rail systems could potentially reduce their net energy consumption on a range varying from 10% to 45% depending on the individual characteristics of the system (Adinolfi *et al.*, 1998; Foiadelli *et al.*, 2006; Kim and Lee, 2009; Falvo *et al.*, 2011; Lee *et al.*, 2011a; López-López *et al.*, 2011; García Álvarez and Martín Cañizares, 2012a).

Additional benefits associated with regenerative braking strategies have been identified. Regenerative braking may mitigate some problems typically related with electrified transport systems such as voltage drops at the feeder lines or high power peak consumptions (Ciccarelli *et al.*, 2012; Iannuzzi *et al.*, 2012a). In rail systems with extensive underground sections (e.g. London), regenerative braking might contribute also to reduce energy consumption in heating, ventilation and air conditioning applications by lowering the thermal loads in tunnels and stations (Thompson *et al.*, 2006; Ampofo *et al.*, 2011).

Despite all the aforementioned advantages of regenerative braking, recovered energy is still mainly dissipated in electrical resistors and only a small portion is used to supply the vehicle auxiliary systems or returned to the network. While it is difficult to ascertain specifically, a plausible explanation for this practice is the lack, until recently, of widespread availability of technologies enabling efficient management of regenerative braking in urban rail systems. This might be acting as a barrier for stakeholders (e.g. operators and local authorities) to make investment decisions given the lack of proven experience and track record on the actual, rather than estimated contribution of such systems in increasing energy efficiency.

4.4. Strategies for maximising exchange of regenerative energy between vehicles

Network receptivity has been highlighted as one of two distinct and significant approaches identified for maximising the use of the recovered energy. Barrero *et al.* (2010) defined network receptivity as the ratio of the total energy returned back to the line over the possible energy (kinetic and potential) that could be regenerated in the braking process.

Considering that the possible energy recovery mainly depends on the topography (e.g. track profile) and the duty cycle (e.g. frequency of stops), consequently being unique and fixed for every single system, a forthright approach to improve line receptivity is to increase the number of trains accelerating and braking simultaneously. If a vehicle decelerates while another accelerates in the same electric section, the regenerated energy can be directly transferred between both trains through the power supply line, as illustrated in Figure 17.

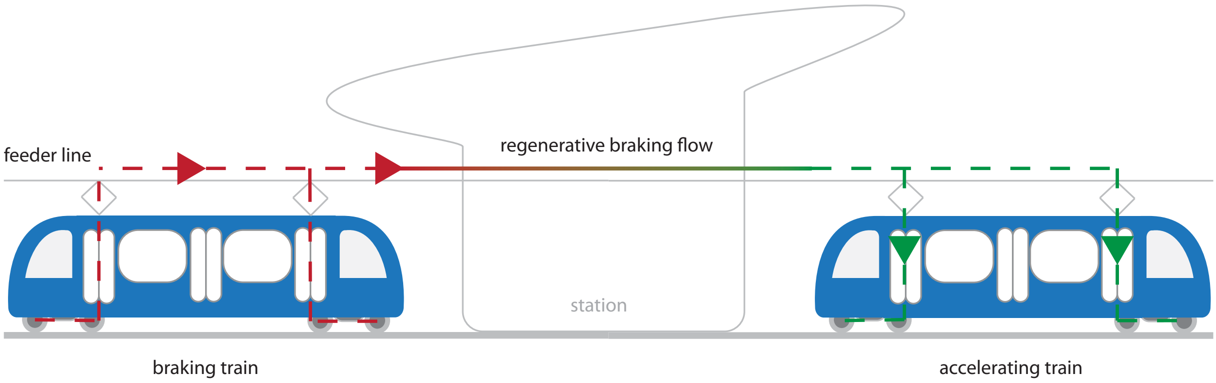

Figure 17. Schematic representation of regenerative energy exchange between trains.

Careful planning design of the operation schedule of trains may therefore lead to significant energy consumption reduction and hence conservation in the whole system while maintaining overall performance in terms of service output. Timetable optimisation in addition, may also limit the simultaneous acceleration of too many vehicles, thus reducing maximum traction power which are associated with consumption peaks and consequently the levels of investment and operational costs (Albrecht, 2004; Chen *et al.*, 2005).

There is evidence in the literature supporting the benefits of timetable optimisation for energy efficiency purposes. For instance, Nasri *et al.* (2010) proposed a timetable optimisation method based on a genetic algorithm aimed at maximising energy exchange between vehicles in a metro system. Based on their model, the authors reported energy consumption reduction of up to 14%. The optimisation method suggested was anchored on determining the optimum values of the reserve time that maximise the use of regenerative braking. The authors went on to consider other parameters such as the influence of headway time but, although this particular parameter has a significant influence on energy recovery, it is much less flexible than dwell time and usually limited by traffic demand and operational restrictions. A different approach to achieve timetable optimisation aiming at maximising the regenerative energy exchange between vehicles was proposed by Peña-Alcaraz *et al.* (2011) based on a timetable model stated as a mixed-integer optimisation problem synchronising acceleration and braking processes of vehicles in the same electrical section. The authors focused on increasing the exchange of recovered braking energy during off-peak hours, when the likelihood of having simultaneous acceleration and braking processes is much lower. The proposed timetable was trialled on the Madrid metro system (Line 3) yielding a measured mean energy saving of 3% after one week. The authors went on to stress that these results were obtained with a timetable modification of less than a minute with respect to the original one, forecasting that energy savings could reach up to 7% by slightly relaxing the timetable constraints.

A third and final illustration of timetable optimisation for energy conservation purposes worth mentioning is the case of Rennes metro in France reporting annual energy savings of 12% (Boizumeau *et al.*, 2011). As with other research in the literature, the timetable parameters used for the optimisation process were frequency of service and dwell time at stations. The authors also concluded that the potential energy consumption reduction at high frequency or with low number of trains running were not that significant.

Another aspect to be considered when attempting to maximise exchange of recovered energy between vehicles is the design of driving strategies, which could play a significant role when trying to synchronise departure and arrival of services in urban rail systems. There is evidence that passenger perception of service quality is more negatively affected by extended dwell times at stations rather than overall journey time. This aspect should be taken into account when designing energy-efficient driving strategies to increase energy recovery without compromising service quality (Miyatake and Ko, 2007; Malavasi *et al.*, 2011).

A successful application of optimised timetables as discussed here would require implementation of a real-time control system. Such a system should be able to i) advise drivers on the departure times and driving strategies and ii) enable an automatic recalculation of the schedule to recover from unforeseen events which inevitably take place in everyday operation e.g. delays. The development and implementation of advisory systems, via software technology, requires relatively low investment costs, especially if compared with installation of ESSs or reversible substations. For that reason, optimising timetables should be regarded as one of the first options to take into consideration when aiming at increasing the benefits of regenerative braking in urban transit systems. Installation of ESSs and reversible substations should be considered as an option to recover the amount of energy that other vehicles in the system are not able to absorb.

4.5. Energy storage systems for urban rail application

The advances experienced in technologies applied to energy storage system developments in recent times have been significant e.g. higher capacity, making them financially viable and commercially available. These have lead to the achievement of greater energy efficiencies (Meinert *et al.*, 2015). This fast and outstanding development of both energy storage technologies and power electronics converters has enabled ESSs to become an excellent alternative for reusing regenerated braking energy in urban rail system (Rosen, 2012). Energy storage systems can be broadly defined into two areas of application based on whether they are installed either on board vehicles or at the trackside. On-board ESSs permit trains to temporarily store their own braking energy and re-utilise it in the next acceleration stages or for other on-board purposes e.g. HVAC. On the other hand, stationary ESSs absorb the braking energy of any train in the system and deliver it when required for other vehicles' acceleration.

4.5.1.Energy storage systems characterisation

The structure of energy storage systems typically consists of three main components, irrespective of their application (i.e. mobile or stationary) namely the energy storage device itself, a power converter to condition the input and output electrical flows and a controller managing the charge and discharge processes, as shown in Figure 18.

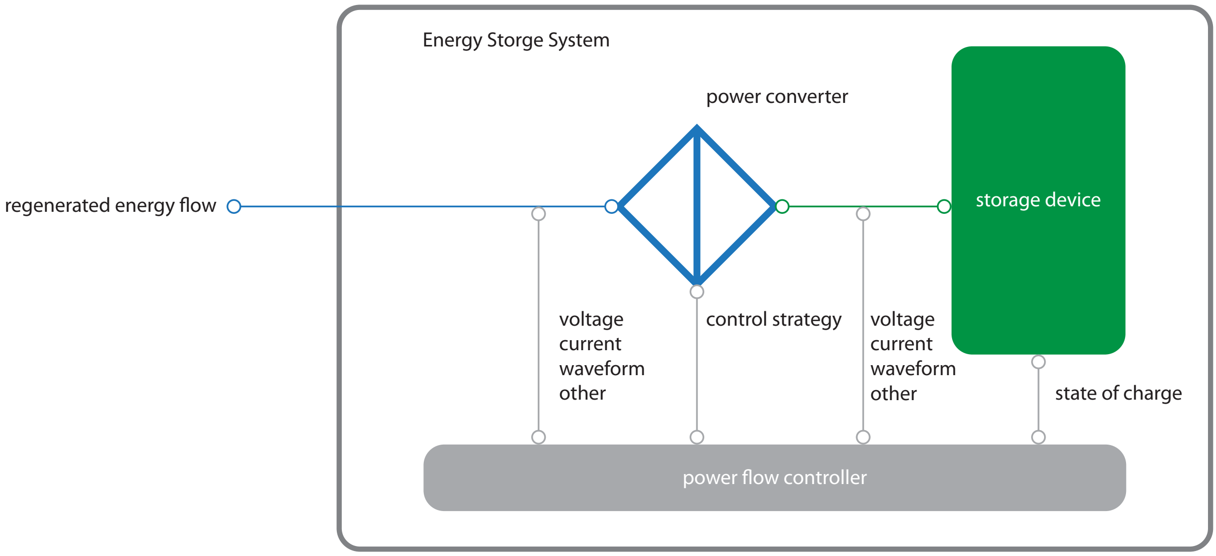

Figure 18. Internal structure of an ESS for railway application

The operational conditions dictated by urban rail systems can be translated into a generalised set of requirements for potential energy storage systems as summarised in Table 10.

ESS feature requirement	Description and observations
Large number of cycle loads	100,000 to 300,000 per year depending on the characteristics of the transport system
High power peaks of charge/discharge	Typically between 0.1 and 10MW depending on transport system and whether stationary or mobile applications are considered
Intermediate energy capacities	In the case of on-board systems the required storage capacity may be high;
Reduced weight and volume	Of particular relevance for mobile systems.

Table 10. Summary of key general features required for ESSs in urban rail applications (Steiner and Scholten, 2004; Schroeder *et al.*, 2010; Vazquez *et al.*, 2010)

The input and output conditions of the majority of readily available energy storage systems differ from those required by rail networks, making it necessary to use power conversion systems for efficient functioning of the ESS. Power converters consist of electronic devices that adapt the characteristics of the electricity regenerated in the braking process to the working conditions of the energy storage device i.e. voltage, current and/or waveform. Their detailed topology depends on the storage technology used and the specific application envisaged. Power converters are required to efficiently manage the energy flow in a bidirectional way and must have a small size and light weight, especially in mobile applications. An overview of the most commonly used topologies for power converters can be found in Vazquez *et al.* (2010). Irrespective of the technology selected for the energy storage device, power flow controllers are needed to optimise the ESS performance. These controllers must manage the charging and discharging cycles according to several parameters such as the state of charge (SoC) or the network voltage. In general terms, ESSs are charged only when voltage at the contact line is above the threshold value, which means that no more regenerated energy can be absorbed by the feeder network.

4.6. Energy storage technologies for urban rail applications

The requirements summarised in Table 10 can be met to different levels of accuracy by a number of key relevant technologies. Four of these are described in detail below, followed by an assessment of their suitability based on a technical and economical comparison.

4.6.1. Electrochemical double layer capacitors

Electrochemical double layer capacitors (EDLC), also known as ultracapacitors or supercapacitors, consist of storage devices that essentially work under the same principle as conventional electrolytic capacitors: Energy is stored in an electrostatic field by simple charge separation and no chemical reactions take place. EDLCs are characterised by a very large electrode surface area, a high permittivity and an extremely small charge separation, which gives them an outstanding energy density compared with conventional capacitors.

EDLCs present very low internal resistance and consequently have very high efficiencies, typically around 95%. This is due to the lack of chemical reactions on the electrodes. In addition, EDLCs allow very fast charge–discharge processes with high currents (see Table 12 for more details) as well as being able to be completely discharged and work in a wide range of environmental conditions (Sharma and Bhatti, 2010). Interestingly, their lifetime may be as long as 10^6 charge–discharge cycles because of the electrostatic storage process (Hammar *et al.*, 2010). EDLCs have a considerably high power density but, conversely, they present a relatively low energy density (Burke and Miller, 2011). Another advantage is that their state of charge can be easily determined by measuring the terminal voltage. By contrast, EDLC are characterised by high self-discharge rates. Recent research on EDLCs has been focusing on increasing their energy capacity by developing composite and nanostructured materials (Liu *et al.*, 2010; Wang *et al.*, 2012). Thus, it has been reported that the use of carbon nanotubes instead of the usual porous carbon-based materials might lead to increased performance i.e. energy densities of 60Wh/kg and power densities of 100 kW/kg (Hadjipaschalis *et al.*, 2009). Alternatively, the relatively recent development of lithium-ion EDLCs may lead to increasing operating voltages as well as higher energy and power densities (Lambert *et al.*, 2010; Manla *et al.*, 2011; Ciccarelli and Iannuzzi, 2012).

These characteristics of EDLCs make them a very suitable option for energy storage in both railway and power applications. Their rapid response capability make them suitable to be effectively used for supplying power peak demands and for voltage stabilisation purposes. Power flows conversion and management is however essentially required to achieve an optimum performance in those functions (Coppola *et al.*, 2012). Nevertheless the configuration of the converter strongly influences the efficiency and final size of the system. According to Douglas and Pillay (2005), the number of EDLCs in an ESS may be minimised by operating them at their highest current rate, although this approach leads to greater size and weight of the associated power electronics. On the other hand, the lower the current through the cells, the higher is the storage efficiency (Barrero *et al.*, 2008).

4.6.2.Flywheels

Flywheels are electro-mechanical devices that store kinetic energy in a rotating mass known as rotor. The stored energy is proportional to the inertia of the rotor and to the square of its rotational speed. Whereas early systems used large steel masses rotating on mechanical bearings, the newer generation of flywheels is made of carbon-fibre composite rotors suspended by magnetic bearings (Bolund *et al.*, 2007). The use of light composite materials reduces the inertia of flywheels but allows much higher rotational speeds because of their significantly higher tensile strength (Tzeng *et al.*, 2006). Magnetic bearings, in turn, offer very low friction enabling a considerable reduction of internal losses during long-term storage (Abrahamsson and Bernhoff, 2011). All of the components of a flywheel are typically mounted in vacuum enclosures so that friction losses are minimised. Notwithstanding, due to the complexity associated with vacuum systems, other alternatives such as using helium–air mixture gas have been proposed in the literature to reduce the windage loss (Suzuki *et al.*, 2005).

The operating principles of a flywheel require the rotor to be connected to an electrical machine than can operate either as a motor or as a generator. Specifically, it acts as a motor in the charging process, when the electrical supply is used to increase the kinetic energy of the flywheel by speeding up its rotational speed. On the other hand, the electrical device performs as a generator when the flywheel releases the stored energy. In this case, the applied torque will decrease its rotational speed. The need for an effective system to transform and control both the input and output power flows has strongly limited the application of flywheels in high power applications for many years (Jefferson and Ackerman, 1996). Nevertheless, the advances in power electronics are facilitating a reliable and efficient operation of flywheels at high power rates.

A significant advantage of flywheels is that they allow a fast charge–discharge process for a potentially infinite number of cycles. Additionally, they present relatively high overall efficiencies and elevated energy and power densities (see Table 12 for more details). Other relevant characteristics of flywheels include the measurability of their state of charge as a function of angular velocity, their wide range of operational temperature and their use of low environmental impact materials. These advantageous features make ESS based on flywheels a very suitable option for different applications such as transportation or quality power applications (Richardson, 2002; Lawrence *et al.*, 2003; Werfel *et al.*, 2007; Flynn *et al.*, 2008; Park *et al.*, 2008; Liu *et al.*, 2010).

Nonetheless, flywheels present a number of drawbacks that hinder their extensive use in railway applications. First, they have a potential risk of explosive shattering in case of catastrophic failure, for example due to overload. Although modern fibre-reinforced composite rotors fail in a less destructive manner than metallic ones (Thompson *et al.*, 2005), and despite the fact that they are typically protected by a multiple-barrier containment system in which the vacuum chamber acts as the first safety enclosure, this potential danger is regarded as a major safety issue in public transport applications. Their relatively high weight is another handicap for the use of flywheels in vehicles. A final main disadvantage is that flywheel technology is characterised by high self-discharge rates, which is caused by different factors such as internal friction or orientation changes produced by vehicle movements.

4.6.3. Batteries

These devices store and deliver energy by means of reversible electrochemical reactions taking place between two different materials known as electrodes immersed in an electrolyte solution. These reactions occur inside cells, which are the basic units forming a battery. Depending on the core chemistry used, batteries may offer a wide range of operational characteristics. A brief description of the most common and promising battery configurations available for energy storage in urban rail systems is given in Table 11.

Battery technology	General description	Main advantages	Main disadvantages	Application	References
Lead-acid	These are the oldest and most extensively used rechargeable electrochemical devices. In charged state the electrodes are made of lead metal and lead oxide, while a diluted sulphuric acid solution acts as electrolyte. In the discharged state both electrodes turn into lead sulphate and the electrolyte becomes primarily water.	Relatively low costs, high reliability and efficiency, low energy density and relatively high power density when compared with other batteries. Very low self-discharge rates.	Poor low temperature performance, requiring therefore a thermal management system. Inability be completely discharged plus negative influence on the environment due to lead processing.	Cost sensitive applications where limitations do not represent an issue. Regarding railway systems, they can be found mainly in back up applications.	Railway Gazette (2010c); Kirchev *et al.* (2011); Czerwiński *et al.* (2012)
Nickel-based	Nickel–cadmium (NiCd) and nickel metal hydride (NiMH) are the most common nickel-based batteries. Both types use nickel hydroxide as a positive electrode and an alkaline solution as electrolyte. As for the negative electrode, the NiCd type uses cadmium hydroxide whereas the NiMH technology has a metal alloy capable of absorbing and desorbing hydrogen. They have a robust reliability and require low maintenance.	Compared to lead–acid, NiCd batteries have higher energy and power densities, as well as larger lifespan. NiMH batteries offer higher energy and power densities, longer lifespan, reduced memory effect and avoid the use of toxic cadmium.	NiCd cost is considerably higher, present lower efficiency and self-discharge rates are much higher than for lead–acid batteries. The efficiency of NiMH is not particularly high and they present a very high the high self-discharge rate. However, the introduction of novel separators might mitigate this issue.	In railway applications, NiCd batteries have been mainly used as backup for auxiliary systems. In traction functions, they have been superseded by NiMH.	Kritzer (2004); Railway Gazette (2009a)

Lithium-based	Based on the migration of lithium ions between the electrodes through the electrolyte. Lithium-ion (Li-ion) and lithium-polymer (Li-poly) represent the major families of cells. The primary difference between them is that in Li-poly batteries the electrolyte (lithium salts) is held in a solid polymer composite instead of an organic solvent.	Relatively high energy and power densities, high efficiency, low self-discharge rate, elevated number of cycles, no memory effect and extremely low maintenance	Need a management system to maintain working temperature, voltages and SoC within a safe and efficient range of operation. High cost due to special packing and protection circuits. Flammability risk (Li-ion > Li-Poly). Lower temp range of operation (Li-Poly) and significant shorter lifetime.	Widely used in portable equipment such as laptops or mobile phones, but due to the outstanding progress achieved in terms of energy and power densities, they represent a very promising option for hybrid and electric vehicle applications, power quality support or even aerospace applications.	Marsh *et al.* (2001); Chen *et al.* (2009); Nasri *et al.* (2010); Kushnir and Sandén (2011); Rao and Wang (2011); Zhang and Lee (2011); Brutti *et al.* (2012); Mukherjee *et al.* (2012)
Sodium-based	Based on the movement of sodium ions between both electrodes. Sodium sulphur (NaS) uses molten sulphur as positive electrode and a solid beta alumina ceramic as electrolyte, sodium nickel chloride (known as ZEBRA) uses nickel chloride and liquid sodium chloroaluminate, respectively.	NaS are highly energy efficient, have a rather long cycle life and offer relatively high energy and power densities. ZEBRA improve NaS safety characteristics and cell voltage.	High self-discharge ratios as part of their stored energy are used to maintain high working temperatures (300^{o} C). Lower energy density and lower power density.	Large-scale stationary systems like power quality and peak shaving applications	Ellis and Nazar (2012)

Table 11. Common battery configurations overview

In addition to the configurations described in this table, there are other emerging battery technologies currently in the research domain or in the early stages of development e.g. Metal–Air batteries and Redox Flow Storage systems. Metal–Air technology offers high energy densities of up to 3000Wh/kg at reasonable costs, representing a favourable option for a wide range of applications e.g portable electronics and electric vehicles. Nonetheless, extensive research is still needed particularly in areas related to the cathode materials and electrolyte systems to improve their low efficiency (Kraytsberg and Ein-Eli, 2011; Capsoni *et al.*, 2012). Redox technologies e.g. Vanadium Redox batteries (VRB) have important advantages such as no self-discharge, no degradation for deep discharge and long lifecycle. Nevertheless, they still require high investment costs and need further technical development, especially to increase their energy capacity (Joerissen *et al.*, 2004).

4.6.4.Superconducting magnetic energy storage

Superconducting magnetic energy storage (SMES) enables electric energy to be stored in the magnetic field generated by a direct current flowing through a coil cryogenically cooled below its superconducting critical temperature. The current circulates indefinitely in the coil due to the nearly zero resistance of the superconducting cables, which are typically made of niobium-titanium (NbTi) (Luongo, 1996). The stored energy is released when the DC potential is removed. In order to maintain the superconducting state of the coil, it is immersed in liquid helium contained in a vacuum-insulated cryostat. Similar to other energy storage technologies, SMES need a dedicated power conversion system conditioning the input and output electric flows (Han and Karady, 1996). The main advantages of SMES systems are their great energy storage efficiency and very fast responses (see Table 12). Additionally, they can be almost completely discharged and present a very high cycle life. Their major drawbacks are high investment and operational costs due mainly to the refrigeration system. Another serious issue reported is the strong magnetic fields generated by these kinds of systems, especially when very large capacities are involved. SMES systems have been mostly used for network stability applications (Hsu and Lee, 1993; Sutanto and Cheng, 2009). However, their features make them potentially suitable for railway applications as well, especially for the case of stationary ESSs (Suzuki *et al.*, 2004; Ise *et al.*, 2005).

4.6.5.Comparison and assessment

The previous sub-sections (4.6.1-4.6.4) have presented the main characteristics of the most common and suitable technologies used for energy storage, including the main advantages and drawbacks as well as typical applications. In order to compare and assess their suitability for energy storage in urban rail applications, these technologies have been evaluated based on a seven parameter criteria i.e.

i) technical maturity, ii) energy and power density, iii) time of discharge, iv) efficiency of discharge, v) self-discharge rate, vi) durability, vii) capital cost. Their main features according to these parameters are summarised in Table 12.

ESS	Maturity	Energy and power density			Discharge time (miliseconds_ms seconds_s; minutes_min; hours_h;)	Efficiency (%)	Self-discharge (daily % of rated capacity)	Durability (No. of cycles)	Capital cost	
		Wh/kg	W/kg	kWh/m^3					$/kWh	$/kW
Lead-acid	Y	20-50	25-300	50-80	s-h	70-90	0.05-0.3	200-2000	50-400	300-600
Ni-Cd	Y	30-75	50-300	60-150	s-h	60-80	0.2-0.6	1500-3000	400-2400	500-1500
NiMH	Y	60-80	200-250	100-150	s-h	65-70	1-2	1500-3000	400-2400	-
Li-ion	Y	75-200	100-350	150-500	s-h	90-100	0.1-0.3	1000-10,000	500-2500	1200-4000
Li-Poly	Y	100-200	150-350	150-200	s-h	90-100	0.15	600-1500	900-1300	-
NaS	Y	120-240	120-230	110-250	s-h	75-90	20	2000-3000	300-500	1000-3000
ZEBRA	Y	100-120	150-200	120-180	s-h	85-90	15	>2500	100-200	150-300
flywheel	Y	5-100	1k-5k	20-80	ms-min	90-95	100	$<10^7$	1k-5k	250-350
EDLC	Y	2.5-15	500-5k	10-30	ms-min	90-100	20-40	$<10^6$	300-2k	100-300
SMES	N	0.5-5	500-2k	0.2-2.5	ms-s	95-100	10-15	$>10^5$	1k-10k	200-300

Table 12. Consolidated main features of major ESS technologies for urban rail application (Dustmann, 2004; Kritzer, 2004; Ibrahim *et al.*, 2008; Chen *et al.*, 2009; Hadjipaschalis *et al.*, 2009; Kadhim, 2009; Hammar *et al.*, 2010; Vazquez *et al.*, 2010; Burke and Miller, 2011; Rahman *et al.*, 2012)

Technical maturity

Lead–acid batteries are the most mature technology as they have been used in a variety of applications for over 100 years. NiCd batteries can be regarded also as a completely established storage technology. In turn, NiMH, lithium-based and sodium-based batteries can all be considered proven technologies already available on the market. Despite the significant improvements experienced in recent years, flywheels and EDLCs are based on very well known technologies and therefore they can be considered mature technologies. As for SMES systems, they have been demonstrated to be technically available but not largely commercialised. Metal–Air batteries and the Redox Flow Storage system are still under development and they cannot be considered commercially mature technologies.

Energy and power density

These are decisive parameters to be considered when selecting storage technologies for railway applications, especially for the case of mobile ESSs where both weight and space are critical. Table 12 shows that batteries present considerably higher energy capacity per unit of weight and volume than flywheels, supercapacitors or even SMES systems. Among batteries, lithium-based technologies offer the greatest energy density range, followed by sodium-based ones. However, lithium batteries present higher compactness (energy per unit of volume), which makes them more suitable for on-board ESSs. On the other hand, the power density offered by batteries is significantly lower than flywheels, supercapacitors or SMES systems. Flywheels and EDLCs present the highest power densities, but the former have slightly higher energy density and compactness.

Time of discharge

This is a fundamental aspect for peak shaving and voltage stabilisation functions. Batteries are clearly disadvantaged in comparison with flywheels, EDLCs and SMES, all of which allow for very fast responses. SMES systems offer the shortest discharge time as they are the only technology to store energy directly into electric current.

Efficiency of charge–discharge cycles

This is an important parameter to consider when evaluating storage technologies as they have a strong influence on the overall system costs. Thus, low efficiencies reduce the fraction of the total stored energy that can be effectively used, consequently increasing the costs of the system. Lithium-based batteries, flywheels, EDLCs and SMES systems offer the highest efficiencies, with values around 95% or above.

Self-discharge rate

Similar to efficiency of charge-discharge, self-discharge rate has a strong influence on the overall system cost which is it crucial when assessing storage technologies. High self-discharge rates reduce the portion of the total stored energy that can effectively be used, increasing the overall system cost. Batteries present much lower values than other technologies with the exception of sodium-based variants. It has been reported that flywheels might completely dissipate their stored energy in one day providing an extreme self-discharge rate that would suggest unsuitability of such systems. However, since urban rail applications involve short storage periods (minutes), elevated self-discharge ratios do not imply serious issues.

Durability

Durability of the ESSs is also a key parameter to consider for the selection of storage technologies as it is directly related to the final costs of the system. This is especially relevant for urban rail applications, where the number of charge–discharge cycles is substantially higher than for other cases. In this regard, from Table 12 it can be concluded that batteries present considerably shorter cycle lives than EDLCs, flywheels and SMES systems, which can last for several hundred thousand cycles. Despite this, modern Li-ion batteries have been reported to offer up to 10,000 cycles.

Capital cost

The capital cost associated with different energy storage technologies is a fundamental parameter affecting the decision making process. Table 12 shows the typical costs per unit of stored energy and per unit of rated power taking into account their efficiency. The costs related to operation, maintenance and replacement of ESS have not been considered. Batteries, especially lead–acid ones, offer the best capital costs per kWh of stored energy. However, when costs per rated power are considered, batteries are considerably more expensive than flywheels, EDLCs and SMES systems.

4.7. On-board energy storage systems

4.7.1.Main characteristics of on-board applications

In previous sections of this chapter, the merits of dynamic braking and regenerative braking have been discussed indicating the suitability of such approaches to produce a significant impact on energy usage of rolling stock and by extension, on the overall energy conservation of the system. On-board ESSs can considerably contribute to this by harnessing the energy recovered and stored during the braking process and making it available to power the vehicle itself during the next acceleration, as Figure 19 shows.

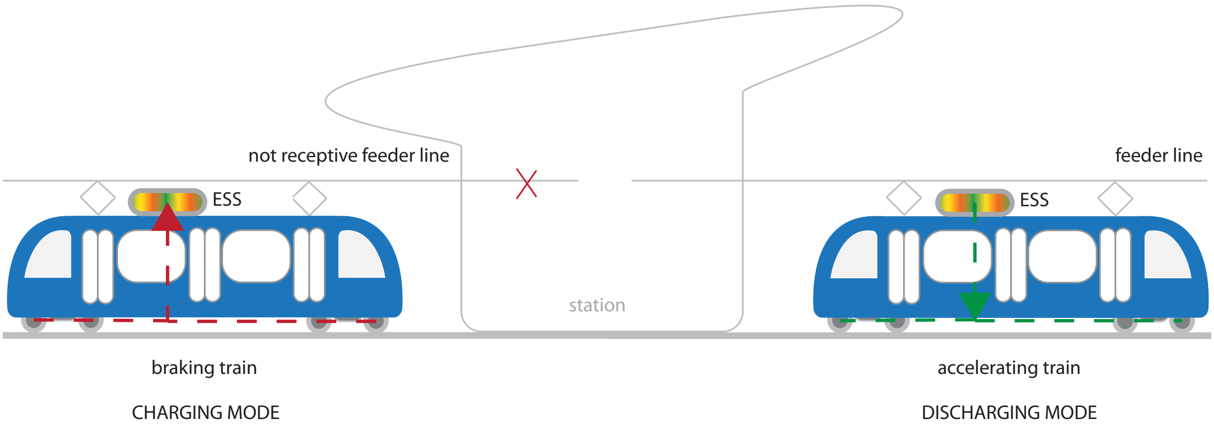

Figure 19. Schematic of operation of on-board ESSs in urban rail systems

Additionally, the integration of on-board ESSs can yield a series of additional benefits at system level, namely i) shaving off power peak demand during acceleration of vehicles, leading to reduced energy costs and minimum resistive losses in the supply line, ii) limitation of voltage drops in the network, allowing for potential higher traffic density without further modification in the existing infrastructure, iii) a degree of power autonomy e.g. in emergency situations, in depot operations or in catenary-free applications such as lines going through historical city centres with restrictions imposed to reduce visual impact.

On-board energy storage systems have a higher operating efficiency than wayside solutions given the absence of line losses. Management of the recovered energy is also simpler since the control is independent of traffic conditions. In contrast, on-board ESSs typically require a large volume in the vehicle introducing a weight penalty. Studies have reported that the additional mass introduced by on-board ESSs increases the traction energy consumption by 1–2% (Meinert, 2009; Domínguez *et al.*, 2011a). This is considered to be one of the main reasons for the preference of installing on-board ESSs on newly designed rolling stock allowing to engineer their integration as part of the whole vehicle design process. Based on the same principle, installation of on-board ESSs when retrofitting existing rolling stock is limited.

Achieving optimal design of on-board ESSs requires an analytical process to find equilibrium between opposing requirements, particularly those related to size. The sizing method for mobile ESSs depends upon their main function i.e. the design requirements differ when aiming at maximising the energy savings, reducing the voltage drops at the line or running the vehicles in free-catenary mode. Oversizing might unnecessarily increase mass and volume of the system, whereas under sizing might lead to considerable energy waste. An established general criteria for energy saving purposes is that the ESS must absorb the maximum amount of braking energy that can be recovered in a sudden braking, assuming that no energy can be returned to the network (Ciccarelli *et al.*, 2012). However, vehicle speeds and occupancy rates are variable, requiring that a careful analysis considering weight and cost options must be carried out to determine the optimum capacity (Barrero *et al.*, 2010). Designing mobile ESSs for voltage stabilisation applications requires the consideration of the operational characteristics of the whole line, e.g. distance between substations and trains timetables (Steiner and Scholten, 2004; Meinert, 2009). When the main purpose of the ESS is to enable catenary-free operation, the system has to be sized to fully drive both traction and vehicle auxiliary systems in the sections without overhead contact line (OCL). In this case, it is also common practice to optimise the driving style so as to minimise the size of the mobile ESS (Meinert, 2009; Ogasa, 2010). Regardless of their main function, on-board ESSs are normally installed together with braking resistors protecting the system when the recovery energy exceeds the designed storage capacity.

Regarding control of on-board ESSs, consideration must be given to different parameters including vehicle speed, state of charge, requested traction power and network voltage. The main aim of control systems is to ensure that ESSs are charged enough to power the vehicle during accelerations and that they remain completely discharged at high vehicle speeds so as to accept the highest amount of energy when braking or at stand-still by charging from the power network.

4.7.2.Technologies for on-board storage systems

Section 4.6 has provided a detailed description of existing energy storage technologies suitable for mobile and stationary urban rail application. Based on this, EDLCs or supercapacitors appear to represent the best option for regenerative energy storage on board rail vehicles given their fast response, high power density and relatively low costs. However, their low energy capacity hinders their use in applications where the main purpose is providing autonomous operation to trains. In this case, Li-ion batteries and to a lesser extent NiMH batteries, might offer better performance, especially if the expected higher power densities and reduced costs are achieved in the near future. The characteristics of flywheels and SMES systems discussed in section 4.6 e.g. risk of explosive shattering in case of catastrophic failure and strong magnetic fields, may not be regarded as suitable options for mobile systems due to safety and operability issues.

The combination of storage systems, particularly batteries and EDLCs appears to be a very promising option for on-board ESSs, especially if operation without overhead contact line is preferred. In this kind of system, EDLCs would absorb the peaks of braking energy providing the needed power for vehicle accelerations. In turn, batteries would absorb the remaining regenerated energy, which would be discharged during the coasting phase of the catenary-free operation. Figure 20 illustrates this process. By following this approach, batteries would be protected against peaks and would suffer much less charge–discharge cycles, which could significantly increase their life and performance (Frenzel *et al.*, 2011; Kuperman and Aharon, 2011).

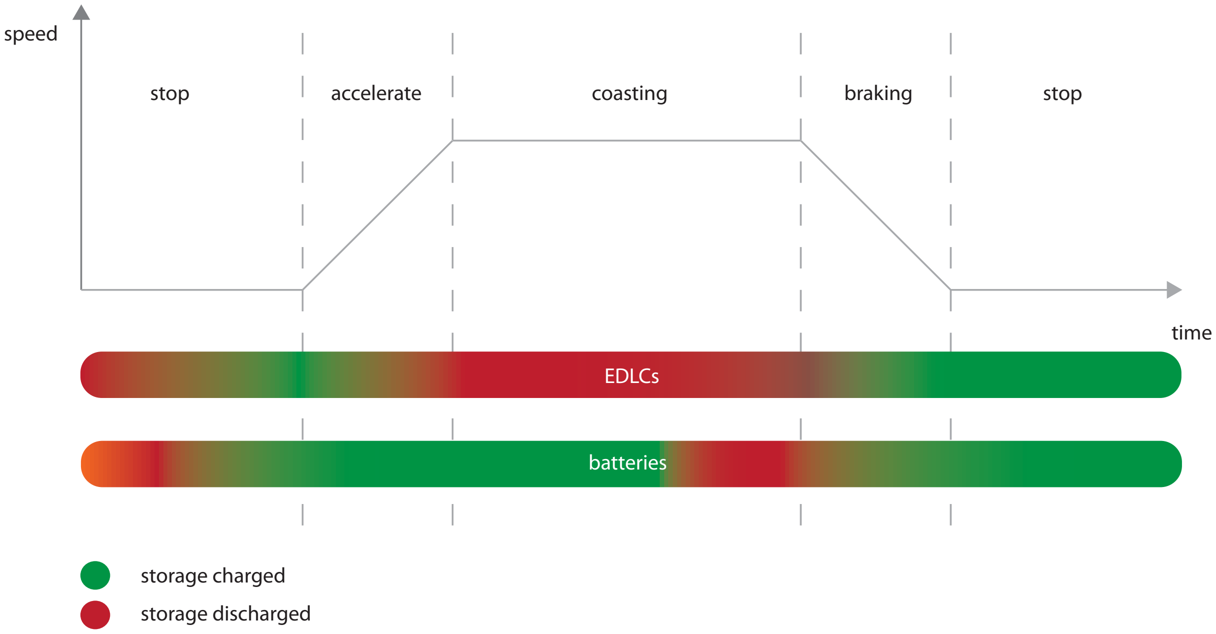

Figure 20. State of charge versus speed profile of a combined EDLC and Battery ESS for catenary-free operation

4.7.3. State of the art assessment of systems for on-board application

Energy storage systems for rail application are still in their infancy. A detailed assessment of the literature available shows however that a number of studies, trials and commercial ventures have been carried out in recent years. Table 13 presents a summary of the most relevant studies published dealing with the storage of regenerative energy on board rail vehicles.

ESS	Study[5]	Main purpose	Main results	Reference
EDLC	T	Design for energy consumption reduction	18-33% Energy savings in a tram line (Brussels)	Barrero *et al.* (2008)
EDLC	T	Sizing for energy consumption reduction	26.3-35.8% Energy savings in a metro line (Brussels)	Barrero *et al.* (2010)
EDLC	T	Assessment of energy consumption reduction	24% Energy savings in a metro line (Madrid)	Domínguez *et al.* (2011a)
EDLC	T	Assessment of energy consumption reduction	30% Energy savings in Blackpool tramway system	Chymera *et al.* (2008)
EDLC	T	Control of energy consumption reduction	Method validation by means of simulations	Miyatake and Matsuda (2009)
EDLC	T/E	Control for energy savings and voltage stabilisation	Method validation at laboratory level 12% energy savings	Ciccarelli *et al.* (2012)
EDLC	T/E	Assessment of energy consumption reduction	19.4-25.6% Energy savings in Mannheim tramway	Destraz *et al.* (2007)
EDLC	T/E	Control for energy consumption reduction	Method validation at laboratory level 38% energy savings	Iannuzzi and Tricoli (2012)
EDLC	T/E	Sizing and control for power peak reduction	Method validation at laboratory 50% power peak reduction 30% energy recovery	Iannuzzi and Tricoli (2010)

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[5] Theoretical studies are noted as “T” and experimental studies as “E”

EDLC	T/E	Control for power peak reduction	Method validation by means of simulation and laboratory tests	Iannuzzi and Tricoli (2011)
EDLC	T/E	Development for catenary-free operation	Validation in real tram system	Mir *et al.* (2009)
EDLC	T/E	Development for catenary-free operation	Preliminary test results at laboratory level	Allègre *et al.* (2010)
EDLC	T/E	Testing MITRAC™ energy saver	30% energy savings in Mannheim LRV system	Steiner and Scholten (2004); Steiner *et al.* (2007)
			50% power peak reduction	
EDLC	T/E	Development for energy consumption reduction	Method validation at laboratory level	Lhomme *et al.* (2005)
EDLC	E	Development for energy consumption reduction and catenary-free operation	16% energy savings in a tram line (Paris)	Moskowitz and Cohuau (2010)
			300m autonomy	
Flywheel	E	Development for energy savings	Prototype construction	Henning *et al.* (2005)
Li-Ion	T/E	Development for energy savings	30% energy savings in a light rail line (Sapporo)	Ogasa (2010)
Li-Poly	T	Development for catenary-free operation	Simulation-based validation of the system	Jeong *et al.* (2011)
EDLC+NiMH	E	Testing Sitras® hybrid energy storage (HES)	10.8% energy savings in LRV system (Lisbon)	Meinert (2009)
			2.5 km autonomy	

Table 13. Summary of key findings of the literature assessment related to the development and application of on-board ESSs in urban rail systems

At first glance, it can be seen that the great majority of studies and interventions focused on the application of EDLC technology. This may be seen as an indicator that this technology have been considered as the most suitable option for mobile applications. Regarding the use of on-board flywheels in urban rail, the literature (academic and grey[6]) is scarce. The work by Henning *et al.* (2005) included in Table 13 reported on the construction of a prototype for hybrid light rail vehicles fitted with a 250 kW high speed carbon fibre flywheel with 4 kWh of effective energy storage capacity. The prototype was intended to be roof-mounted, but no results of real application have been reported. A similar system has been reported for a different vehicle type and manufacturer but no application results have been published either (Lacôte, 2005; Ogasa, 2010). Rupp *et al.* (2016) recently published the outcomes of the potential benefits that could be introduced by using ESSs based on flywheels in a light rail vehicle part of the Edmonton (Canada) urban rail system. The authors developed a mathematical model predicting energy capacity, power and cost of the ESS to estimate the potential energy and cost savings. The research included design aspects for the ESS, particularly energy capacity and rotor geometry using a previously developed framework for such purpose (Krack *et al.*, 2010). The results predicted energy savings ranging from 9.83% to 31.21% and costs reduction on a 0.55% to 11.09% bracket for the specific vehicle and system characteristics used (Edmonton). The manufacturing aspects of flywheel ESSs applied to suburban rail vehicles have been discussed by Li *et al.* (2012b) although no clear outcomes were reported regarding its operation and savings potential.

The use of batteries as on-board ESSs has not been extensively discussed in the scientific or industrial (grey) literature. Their low power density and short lifecycle seems to be the main reason for the relatively low implantation of such technology on its own. Nonetheless, there are interesting and relevant recent studies revealing promising results for the application of lithium-based batteries on board. The Railway Technical Research Institute (RTRI) in Japan has developed and successfully tested in the city of Sapporo a hybrid electric light rail prototype incorporating a Li-ion battery to recover braking energy, reporting savings of up to 30% (Ogasa, 2010). Similarly, the Korea Railroad Research Institute (KRRI) has designed a low-floor Light Rail Vehicle (LRV) with Li-poly batteries on board to recover braking energy allowing for a catenary-free operation (Jeong *et al.*, 2011). Several simulations have assessed the performance of this system, but no results of real operation have been published. Ceraolo and Lutzemberger (2014) developed a simulation model applied to the tram system in the Italian city of Bergamo exploring the potential benefits of introducing ESS using high power Lithium batteries or EDLCs, both for on-board and stationary application. The authors focused on

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[6] For the purpose of this thesis, grey literature is considered to be those publications that are not in the traditional academic peer-reviewed literature e.g. trade publications and commercial information.

control strategies and cost/benefit aspects, concluding that these were suitable technologies.

The combination of two or more technologies is commonly known as hybrid ESSs. While there are a small number of configurations currently in service for urban rail applications, the take up is still limited which is reflected in the literature available e.g. Meinert (2009) reported the outcomes of in-service measurements of using a EDLC-battery hybrid ESSs in a light rail network south of Lisbon, Portugal. Meinert *et al.* (2015) discussed the merits of combining technologies for on-board ESS but while the authors considered suburban application, the focus was on diesel-driven vehicles rather that fully electrified networks.

The assessment of the literature has provided a clear indication of the high potential and benefits of using energy storage systems for urban rail applications. This has led key manufactures and stakeholders in the industry to seek the introduction of such systems as part of their offer. Table 14 summarises these ESSs showing that there is a clear trend towards the use of EDLCs.

Brand name	Manufacturer	ESS	Application in urban rail	Reference
MITRAC™ Energy Saver	Bombardier	EDLC	LRV in Mannheim (2003-07)	Steiner and Scholten (2004); Steiner *et al.* (2007); Railway Gazette (2008); Bombardier (2009); Railway Gazette (2010a)
			Rhein-Neckar region (2013-today)	
Sitras® MES	Siemens	EDLC	Innsbruck tramway	Siemens (2011; 2012b)
ACR	CAF	EDLC	e.g. Seville, Saragossa	CAF (2011)
STEEM	Alstom	EDLC	Paris tramway (2009-10)	Moskowitz and Cohuau (2010); Alstom (2011)
-	Alstom-SAFT	NiMH	Nice tramway (2007-today)	Railway Gazette (2006); Moskowitz and Cohuau (2010); Ogasa (2010)
LRV Swimo	Kawasaki	NiMH	Prototype tests in Sapporo (2007-08)	Kawasaki Heavy Industries (2008); Ogasa (2010)
LFX-300 streetcar	Kink Shayro	Li-ion	Prototype test in Charlotte (2010)	Railway Gazette (2011b)
Sitras® HES	Siemens	EDLC+NiMH	MTS light rail system, Lisbon (2008-today)	Meinert (2009); Siemens (2012a)

Table 14. Summary selection of relevant ESSs available in service

Thus, Bombardier developed an EDLC-based system for recovering braking energy in LRVs, metro trains and diesel multiple units, branded MITRAC™ Energy Saver. After being successfully tested in revenue service, the system is currently available as a standard solution for their light rail vehicles (FLEXITY 2). Similarly, Siemens has developed the Sitras® MES (Mobile Energy Storage) system for braking energy storage in electric and diesel rail vehicles. According to the manufacturer, the system has been used to retrofit Innsbruck tramway (Austria) in 2011, but no operational results have been published thus far. Another EDLC-based ESS available on the market is the ACR system (Rapid Charge Accumulator) developed by CAF. This system has been successfully tested on a CAF Urbos-2 vehicle in Seville, and is currently available as a standard option in the Urbos-3 trams (e.g. Saragossa). Lastly, Alstom has developed the STEEM (Maximised Energy Efficiency Tramway) system aimed at increasing the energy efficiency in tramway systems while allowing catenary-free operation. This solution was tested on a RTPA tramway (Paris) in regular operation from May 2009 to September 2010. However, no results of commercial application have been reported thus far.

For applications where relatively long distances of catenary-free operation are required e.g. historical city centres, battery-based solutions have been preferred. In this regard, Alstom has equipped twenty Citadis trams in the city of Nice (France) with on-board NiMH batteries developed by Saft. This ESS enables a catenary-free operation in two non-electrified sections of about 450 m in the historical city centre. In turn, the Japanese manufacturers Kawasaki and Kinki Shayro have developed new hybrid electric vehicles for operation without OCL: Swimo (NiMH batteries) and LFX-300 (Li-ion batteries), respectively. In both cases, the batteries are able to absorb the regenerative braking energy, but they are mainly recharged through the feeder line during stops.

A different approach for catenary-free operation of light rail vehicle has been proposed by Siemens, which has developed a hybrid ESS branded Sitras® HES. The system consists of a Sitras® MES mobile energy storage unit and a traction battery made of NiMH cells provided by Saft. This solution has been tested in passenger operation in Lisbon since 2008 with very promising results. Currently, both Sitras® MES and Sitras® HES energy storage systems are optional components of Siemens' Avenio tram platform.

In addition to these examples of pioneering applications, a number of interventions have been reported recently (Railway Gazette, 2016) in cities across the word using these core commercial technologies e.g. Qatar, Doha, Portland (Siemens), Budapest, Kaohsiung-Taiwan (CAF), Rio de Janeiro (Alstom) showing the rapid acceptance of ESS for urban applications.

4.8. Stationary energy storage systems

This subsection follows the same structure as the previous section 4.7 by providing a description of the main characteristics of stationary or wayside applications, a portrayal of the main technologies applicable and an overview of the most relevant results available in the literature illustrating their potential.

4.8.1.Main characteristics of stationary applications

It has been described in previous sections how energy recovery works, reusing it usually by transferring it to a vehicle in the vicinity, following a syncronised approach e.g. timely braking and accelerating phases for both vehicles. Stationary ESSs essentially work absorbing the regenerated braking energy that cannot be used simultaneously in the system. The ESS delivers the stored energy when it is required for the acceleration of any vehicle in its same electric section as illustrated in Figure 21.

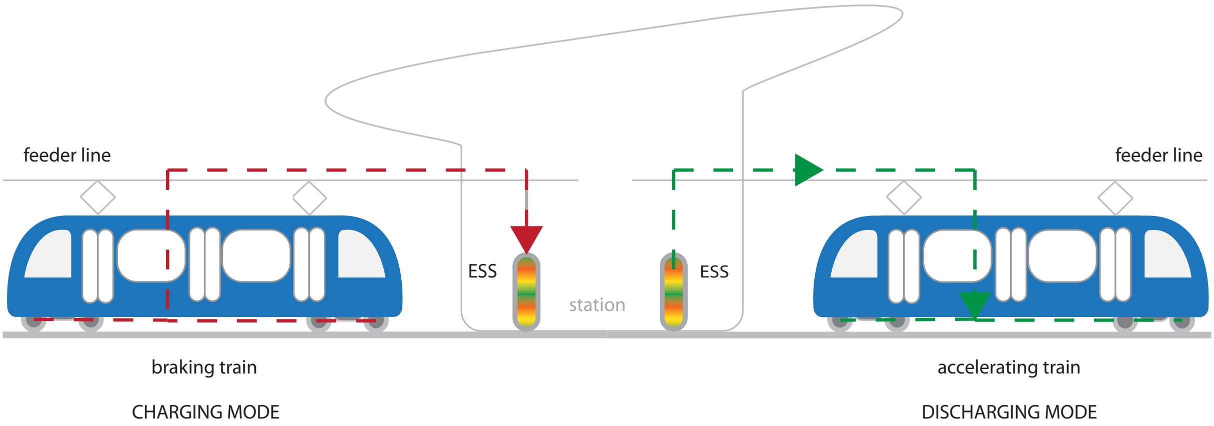

Figure 21. Schematic of stationary ESS operation in urban rail

The charge and discharge processes require an electronic controller that generally operates as a function of the voltage on the line (Konishi *et al.*, 2010) i.e. when an overvoltage takes place as a result of any braking process, ESSs operate in “charging” mode absorbing the excess of regenerated energy on the line; in turn, when a voltage drop is detected, ESSs deliver the stored energy in order to keep the threshold value on the network. Wayside ESSs are usually installed in existing substations or in specific locations where the contact line voltage variations are more significant, for instance near to stations.

Stationary ESSs can be used to reduce the energy demand of the whole system as well as to stabilise network voltage at weak points, which is a major advantage over reversible substations. Moreover, wayside ESSs might eliminate the need for additional feeding substations to compensate the voltage drops typically associated with end of lines (Rufer *et al.*, 2004). Similar to on-board ESSs, stationary devices can greatly contribute to shave off peaks of energy consumption during acceleration of vehicles, which in many cases imply considerable cost savings for operators. In addition, another advantage of this application is their ability to enable trains to reach the nearest station in case of failure of the power supply, increasing the overall system reliability. When compared with on-board devices, wayside systems present the advantage of having fewer restrictions in terms of weight and required space. Moreover, stationary systems can recover energy from several braking vehicles at the same time and their implementation and maintenance do not affect operations. On the contrary, stationary systems are generally less efficient due to transmission losses taking place in the network. This fact, which is directly related to the distance between the braking vehicles and the ESS, makes it indispensable to carry out a careful and detailed assessment to determine the optimal position of the storage devices along the line prior to their deployment (Iannuzzi *et al.*, 2012b).

When designing stationary ESSs, it is also very important to take into account the variability of the traffic conditions (Barrero *et al.*, 2010). Provided the receptivity of the line heavily depends on the frequency of services, the optimal size of the ESS will be different for every scenario. A fine-tuned analysis is therefore required to reach a compromise solution that optimises the capacity of stationary ESSs. In this regard, an optimisation procedure based on a non-linear programming technique has been developed in Battistelli *et al.* (2009). Alternatively, a probabilistic method to size wayside ESSs in metro lines was presented in Brenna *et al.* (2007). The stochastic nature of the design variables has been considered in the sizing methods developed in Battistelli *et al.* (2011) and in Iannuzzi *et al.* (2013), whilst a multi-objective optimisation approach has been suggested in Iannuzzi *et al.* (2013). In turn, a simpler and probably less accurate algorithm based on predicting the maximum instantaneous regenerative energy has been proposed by Teymourfar *et al.* (2012).

On the other hand, sizing wayside energy storage devices is strongly dependent on the main function of the system. A recent project on stationary systems for railway applications concluded that the most practical design strategy is to consider the ESS as a solution for simultaneous problems rather than focusing on a single objective (Schroeder *et al.*, 2010). As a first approach to size and optimise the ESS, the authors of that report suggest using voltage sag design. Then, maximising other simultaneous benefits such as peak power shaving or energy consumption reduction could be considered by varying some design parameters. A voltage sag event occurs when the feeder line voltage drops below a determined level for over 1 ms, becoming one of the most relevant contributors to poor power quality for distribution networks (Cheng *et al.*, 2003). Alternatively, focus could be applied primarily on energy savings and peak reductions, but careful economic analysis would be then required. The Schroeder *et al.* (2010) design guide recommends performing detailed simulations and full-scale tests to obtain the best performance results of stationary ESSs, as each transit system has unique characteristics.

4.8.2. Technologies for stationary storage

Given that ESSs for stationary application have less weight and volume restrictions than mobile systems, the range of suitable storage technologies is wider. EDLCs present excellent characteristics to be used in power shaving and voltage stabilisation functions, but as for mobile applications, their reduced energy capacity could limit their use depending on the specific requirements of each system. In this sense, flywheels can provide similar power capacity to EDLCs, but with slightly higher energy densities. The safety concerns related to flywheels used on-board vehicles are less limiting in wayside applications as they may be installed within heavy containers or even underground. SMES systems appear to be a very suitable alternative for stationary ESSs due to their fast response, but their elevated costs, their high complexity and the associated electromagnetic fields may hinder extensive application. Amongst batteries, sodium-based technology might represent a good solution due to the relatively high power capacities and the reduced capital costs per unit of energy and cycle. Expected advances in Li-ion and NiMH might make them interesting alternatives.

4.8.3. State of the art assessment of systems for stationary application

A detailed assessment of the scientific literature has shown a number of developments of stationary ESSs for urban transport applications, a sample of the most relevant of them are summarised in Table 15.

ESS	Study[7]	Main purpose	Main results	References
EDLC	T	Sizing for energy consumption reduction	16.1-33.4% Energy savings in a metro line (Brussels)	Barrero *et al.* (2010)
EDLC	T	Sizing for voltage stabilisation	Procedure validation by simulating a tramway system	Iannuzzi *et al.* (2012b)
EDLC	T	Sizing for voltage stabilisation	Procedure validation by case study simulation	Battistelli *et al.* (2009)
EDLC	T	Sizing for energy savings and voltage stabilisation	Proposal of a stationary ESS for one metro line in Milan	Brenna *et al.* (2007)
EDLC	T	Sizing for voltage stabilisation	Method validation by case study simulation	Battistelli *et al.* (2011)
EDLC	T/E	Sizing for voltage stabilisation	Procedure validation by simulation and laboratory tests	Iannuzzi *et al.* (2012a)
EDLC	T/E	Sizing for energy savings and voltage stabilisation	Procedure validation by simulation and laboratory tests	Iannuzzi *et al.* (2013)
EDLC	T	Development for energy consumption reduction	25% energy saving in Teheran Metro	Teymourfar *et al.* (2012)
			Return of investment within 10 months	
EDLC	T	Sizing for energy consumption reduction	28% reduction in operational costs, Seoul Metro Line 7	Lee *et al.* (2011b)
EDLC	T/E	Development for voltage stabilisation	Construction of a 400 V prototype	Konishi *et al.* (2004)
			Laboratory based validation	
EDLC	T/E	Development for energy consumption reduction and voltage stabilisation	Validation of 600 V and 750 V DC prototypes in Osaka	Morita *et al.* (2008)
			Laboratory tests for 1,500 and 3,000 V DC systems	

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[7] Theoretical studies are noted as “T” and experimental studies as “E”

EDLC	T/E	Development for voltage stabilisation	Laboratory tests with scaled prototype	Rufer *et al.* (2004)
Flywheel	T/E	Development for power management	Validation of a 150 kW prototype for 3000 V DC lines (Madrid)	Garcia-Tabares *et al.* (2011)
Flywheel	E	Testing a system developed by Urenco	Validation in London	Richardson (2002)
NiMH	E	Testing Gigacell® battery power system	Validation at New York City Transit (NYCT) network	Ogura *et al.* (2011)

Table 15. Summary of key findings of the literature assessment related to the development and application of stationary ESSs in urban rail systems

As in the case of on-board ESSs, it is interesting to note that EDLC has been the preferred technology for stationary systems thus far. Most of the studies dealing with the application of this technology focus on the development of methodologies to obtain optimised ESS designs for urban rail (see Section 4.5.1). Regarding the development of stationary energy storage prototypes based on EDLCs, it is worth mentioning the work of Konishi *et al.* (2004). Following a series of preliminary tests carried out at DC 75 V to compare charge–discharge characteristics of EDLCs and Lithium batteries, the authors of that paper opted for the former technology to develop an ESS for voltage stabilisation purposes. The laboratory tests performed at 400 V revealed very promising results for railway applications. Another interesting work developing EDLC-based wayside systems is that published by Morita *et al.* (2008), where two prototypes built by RTRI were experimentally validated. Rufer *et al.* (2004) propose the design of an EDLC-based storage system for use as a voltage compensation substation in a trolley bus system in Lausanne (Switzerland).

Garcia-Tabares *et al.* (2011) reported on the development of a new flywheel system as part of a project sponsored by the Spanish Administrator for Railway Infrastructures (ADIF) in collaboration with CIEMAT (Spanish Research Centre for Energy, Environment and Technology). The authors of that work claimed that, owing to Joule effect losses in the electric machine and aerodynamic losses in the flywheel, the originally designed capacity of 350 kW and 200 MJ had to be limited to 150 kW and 50 MJ, respectively. The system feasibility was proved in a 3000 V DC network with no train interactions and trials under real traffic conditions took place on Madrid's suburban network (Tobajas, 2016). Another relevant publication dealing with the use of flywheels in stationary systems is Richardson (2002), which reports on the performance results of a flywheel ESS developed by the now defunct company Urenco. Ratniyomchai *et al.* (2014) provide an overview of energy storage systems applied to railway systems citing the work of Okui *et al.* (2010) who reported on ESS advances in Japan and specifically on the successful implementation in 1988 of a pioneering stationary flywheel system in the Keihin Electric Express Railway which has returned a 12% saving in energy consumption.

Regarding battery-based storage systems for stationary applications it is worth highlighting Ogura *et al.* (2011) from the relatively limited academic literature. The authors described the Gigacell® Battery Power System developed by Kawasaki, presenting the experimental results obtained from a pilot project carried out in a 2010 test to determine its performance in real traffic conditions. As shown in Table 16, this commercially available system is based on NiMH technology. Tests conducted at the New York City Transit network demonstrated the capability of the system to capture and manage regenerated braking energy. A summary of this and other selected ESS commercially available are included in Table 16.

Brand name	Manufacturer	ESS	Application in urban rail	Reference
Sitras® SES	Siemens	EDLC	Madrid metro (2003-today) Cologne network (2003-today) Beijing metro (2007-today) Toronto rail transit (2011-today)	Siemens (2011; 2012d; c)
EnerGstor™	Bombardier	EDLC	-	Bombardier (2010)
NeoGreen® Power	Adetel group	EDLC	Lyon tramway pilot (2011)	NeoGreen (2011)
-	Woojin Ind. Systems	EDLC	Gyengsan light rail system pilot (2008-09)	Railway Gazette (2009b)
Envistore™	Envitech Energy (ABB group)	EDLC	Warsaw metro Philadelphia transit pilot (2012)	ABB (2012a; b)
Capapost	Meiden	EDLC	Hong Kong metro	Meiden (2012); Railway Gazette (2012c)
Powerbridge	Piller Power Systems	Flywheel	Hannover metro pilot (2004) Rennes metro pilot (2010)	Boizumeau *et al.* (2011); Balmex (2012)
GTR System	Kinetic Traction Systems	Flywheel	London pilot (2000) New York City Transit pilot (2002) Lyon metro pilot (2003-04)	Richardson (2002); Tarrant (2004); Railway Gazette (2011a)
Regen®	Vycon	Flywheel	L Angeles metro (2014-onwards)	Vycon (2014)
Gigacell®	Kawasaki	NiMH	New York City Transit pilot (2010)	Ogura *et al.* (2011)
B-CHOP	Hitachi	Li-ion	Kobe transit system (2007-onwards) Macau metro system	Konishi *et al.* (2010); Shimada *et al.* (2010); Hitachi (2011); Railway Gazette (2012a)
Intensium Max	Saft	Li-ion	Philadelphia transit system pilot (2012)	Saft Batteries (2011); Poulin *et al.* (2012); Saft Batteries (2013)

Table 16. Summary selection of relevant stationary ESSs available in service

In addition to the Gigacell® system, Table 16 shows just a pair of other battery-based stationary systems, both using Li-ion technology and tested in urban rail systems for braking energy recuperation purposes. Whereas the Hitachi system has been in regular operation in Kobe (Japan) since 2007 (Shimada *et al.*, 2010), the Intensium Max system has been tested in the Philadelphia public transport network within an innovative project launched by SEPTA in partnership with Viridity Energy. This project aimed at recovering the full regenerated energy capability of the line by means of wayside storage and energy return to the main grid (Saft Batteries, 2011; 2013).

However, the clearest conclusion from the summary in Table 16 is that as with on-board applications (see Table 14), EDLCs are the current preferred technology for commercialising stationary ESS. The Sitras® SES (Static Energy Storage) seems to be the most successful system as it has been tested and implemented in a variety of urban rail systems worldwide e.g. Cologne (Germany), Madrid (Spain), Beijing (China), Toronto (Canada). Some of these systems have been reported to bring in considerable benefits e.g. the pilot research in Seoul carried out by the Korean Railroad Research Institute (KRRI) showed overall energy reduction of 23.4% coupled with evidence of contribution to stabilisation of network voltage (Railway Gazette, 2009b). Furthermore, Lee *et al.* (2011b) developed an optimisation algorithm which was applied to five different case studies in Seoul's line 7 using the EDLC ESS system reporting efficiencies improvements of up to 90% translating into operational costs reduction of 27.7%. The authors also confirmed the voltage stabilisation benefits.

An alternative to EDLCs is using flywheels for stationary applications. A number of pilot projects have been deployed in urban rail systems with positive results e.g. Boizumeau *et al.* (2011) reported on a 1 MW unit installed in Rennes (France) metro system. Other cities that have piloted flywheel-based stationary ESSs include London, New York and Los Angeles. The latter for instance have reported savings of up to 20% since installation in 2014 (Vycon, 2014).

4.9. Reversible substations

In addition to energy storage systems, reversible substations can also contribute to harness the energy recovered through dynamic braking. This section discusses the main characteristics of these substations providing also an overview of the main developments in the research and commercial fields.

4.9.1.Main characteristics

In DC networks, substations typically provide electric current only in one direction i.e. power to trains and are not able to drive the electricity generated in the system back to the distribution grid. This is due to conventional substations using diode rectifiers that only permit unidirectional flow of power. In contrast, reversible substations, also known as bidirectional or inverting substations, do include an inverter enabling a bidirectional operation, as illustrated in Figure 22. This allows for any excess energy regenerated by the trains to i) be used elsewhere in the network e.g. lighting, escalators and offices or ii) sold back to the energy provider, depending on the legislation of each country or community (Ortega and Ibaiondo, 2011a). Medium voltage distribution networks (AC) are by their nature receptive.

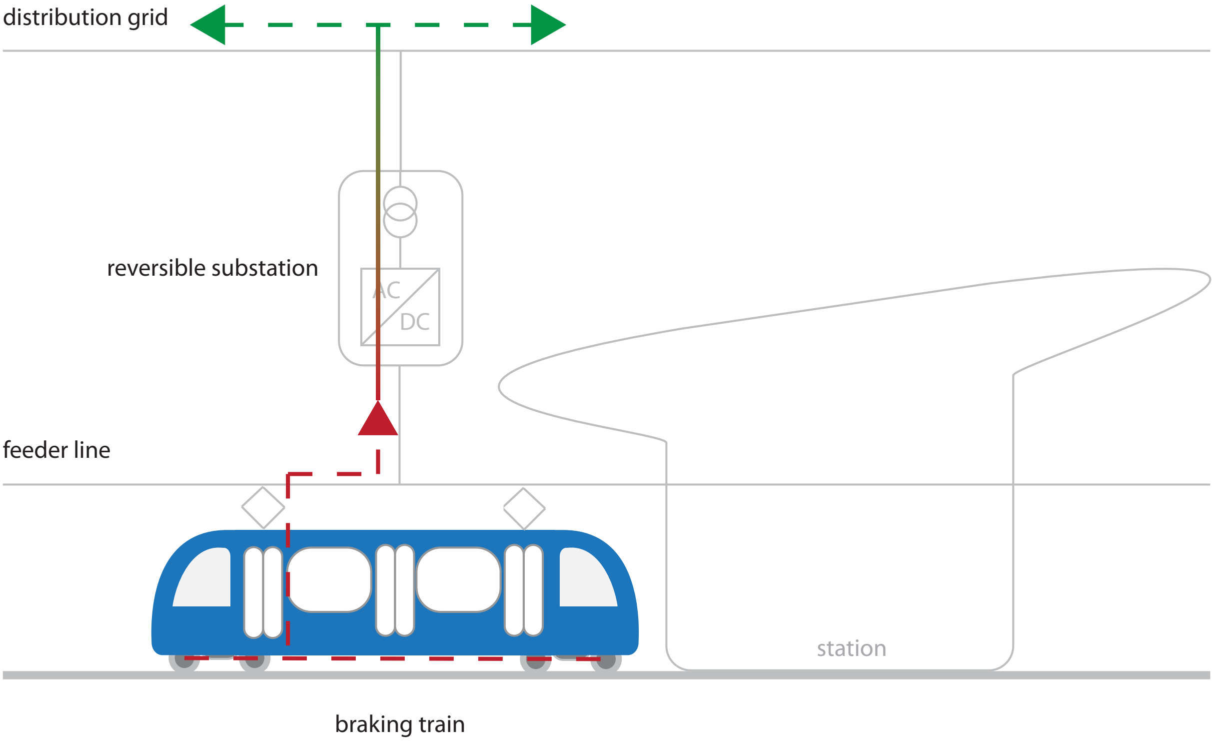

Figure 22. Schematic of a reversible substation in urban rail application

Although the main aim of reversible substations is to maximise the braking energy feedback to the upstream network, they should allow the natural exchange of regenerated energy between vehicles as a priority. Additionally, reversible substations are required to minimise the level of harmonics, ensuring a good quality of power supply in both AC and DC sides. Maintaining the output voltage in traction and regeneration modes to reduce losses is another important function that inverting substations have to meet.

Inverters typically consist of a reversible thyristor-controlled rectifier (RTCR) that enables the current flow to circulate in both directions. In addition to the bidirectional operation, the use of RTCRs instead of common diode rectifiers may provide additional advantages such as better voltage regulation and fault current limiting (Gelman, 2009).

When compared with ESSs, recuperation of braking energy through reversible substations may be considered a more efficient option as they present fewer transformation losses. However, the resistive losses could be relatively high if a detailed analysis for selecting the most adequate locations is not carried out. Other important advantages of reversible substations over ESSs include i) reduced space, ii) lower safety constraints, iii) no exhaustive maintenance is required, iv) implementation, maintenance and repair do not affect operations in the rail system.

As main drawbacks, inverting substations do not permit catenary-free operation of vehicles and cannot be used for voltage stabilisation or peak reduction purposes. In addition, cost is a significant barrier and one of the main obstacles for the use of reversible substations in urban rail systems given the high investment costs associated with their installation. As a way to reduce the payback period, the energy sent back to the grid could be maximised by reducing the interchange of regenerated energy between trains. However, this would require an in-depth economic study considering not only the market energy prices, but also the increase in power consumption due to less energy exchange between vehicles. Interestingly, it has been estimated that the payback period might be less than three years depending on the line configuration (Gelman, 2009) which seems reasonable, both in terms of the accuracy of the estimation and the expected payback timeframe.

4.9.2. State of the art assessment of research and market-ready reversible substations

Determining the optimal number and location of reversible substations requires a complete study and analysis of the entire transport system. For instance, in Mellitt *et al.* (1984) a deterministic technique is proposed to ascertain the optimal capacity, location and control of reversible substations in urban rail systems. Applying the proposed methodology to an existing rapid transit system, the study concluded that the optimal solution was to install thyristor inverters in two of the five substations. Potential energy savings of up to 14% were reported.

A study on the feasibility and the interest of reversible substations as a means to save energy in metropolitan rail systems was presented in Warin *et al.* (2011). This case from French National Railway Company (SNCF) showed that a potential 7% of energy could be sent back to the main distribution grid in the Regional Express Network[8] of Paris.

Regarding reversible substations available on the market, three systems seem to be favoured so far: the HESOP system developed by Alstom, the Sitras® TCI of Siemens and the INGEBER system of Ingeteam. Table 17 summarises their characteristics and location examples.

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[8] Réseau Express Régional (RER)

Brand name	Description	Applications
HESOP	Harmonic and Energy Saving Optimiser (HESOP) is made up of a thyristor rectifier bridge associated with an IGBT converter. In the traction mode, the rectifier transforms AC into DC, while the inverter acts as an active filter. In the recovering or braking mode, the converter regenerates the energy back to the AC side while the rectifier remains inoperative.	Simulation results showed that the HESOP system would improve the receptivity of the Utrecht–Zwolle regional line (The Netherlands) by up to 99%, allowing for energy savings of about 7% in traction consumption. In order to validate the system, two prototype reversible substations were constructed and successfully tested. A four year pilot on the Paris tramway T1 line supported the further development of the technology. London has also successfully implemented them.
Sitras® TCI	TCI is based on the add-on concept i.e. the inverter is installed in parallel with the diode rectifiers commonly used in substations. This enables existing substations acquire the capability to work in reversible mode.	A 750 V system has been tested in the Oslo metro, whilst a customised 750 V solution is being developed for the new Singapore downtown line. The Bayerische Zugspitzbahn Bergbahn railway has implemented a 1,500 V version. This peculiar line presents a great potential for braking energy recovery when the vehicles travel downhill as the slope is up to 25‰.
INGEBER	Aimed at enabling existing DC substations to return the excess braking energy to the general three-phase grid. The system consists of a DC/AC converter installed in parallel to the rectifier of existing substations.	Bilbao (Spain) has been the test bed for this system. A prototype was installed in the metro system in August 2009 fitted on a section with great energy exchange between trains due to the intense transit. Reported savings up to 11% of the substation annual energy consumption.

Table 17. Summary of the main characteristics and implementation examples of three leading reversible substations (Cornic, 2011; Ortega and Ibaiondo, 2011a; Warin *et al.*, 2011; Siemens, 2012e; Alstom, 2016)

In addition it is interesting to highlight a recent project by the Southeastern Pennsylvania Transportation Authority (SEPTA) where the combination of energy storage and return to the main grid has been proposed for the first time (ABB, 2012b). This innovative solution integrates a wayside ESS based on batteries with smart grid technology. The energy flow in the system is managed as a function of the electricity market pricing, the battery state of charge and the availability of braking energy from the trains. The aim of this pilot was to capture the full regenerative capability of the Market-Frankford Line (Philadelphia, USA), reducing the overall power consumption by more than 10% (1200 MWh per year). The success of the pilot has led to further investment on other lines and the whole operation around the system to be a profitable one given energy market prices (Barrow, 2014).

4.10. Chapter conclusions

This chapter has provided a comprehensive overview of the currently available technologies for recovery and management of braking energy in urban rail. Different methodologies to increase the interchange of regenerated energy between trains have been discussed. Additionally, a state-of-the-art review on the energy storage technologies for urban rail applications has been presented. Lastly, reversible substations have been analysed as a means of increasing the braking energy recovery by improving the receptivity of the line. All these have contributed to addressing the first research objective (R0_01) of this thesis seeking to explore how energy is used in urban rail systems. The main conclusions that can be drawn from the chapter are summarised below.

Implementation of timetable optimisation techniques may significantly increase the interchange of regenerated energy between vehicles, therefore reducing the total consumption in the system as well as demand peaks. Energy savings between 3% and 14% have been reported for different urban rail systems analysed in the literature. Since this is a relatively low-cost measure, it could be considered as the first option to increase the amount of energy recovery in urban rail systems. Nevertheless, its application might be limited by service requirements.

The high number of scientific studies, pilot projects and commercially available systems demonstrates that ESSs can be regarded as a valid solution to improve efficiency and reliability in urban rail systems. From the literature assessment, it can be concluded that energy savings between 15% and 30% can be achieved by using energy storage systems. In addition to that, it has been identified that ESSs may mitigate other problems typically associated with urban rail such as voltage drags or pronounced consumption peaks. It has been seen that wayside systems may be more adequate than on-board systems when no operation without overhead contact line is required.

EDLCs, batteries and flywheels are currently the most suitable technologies for ESSs deployed for urban rail applications. Notwithstanding, it has been observed that EDLC-based systems have been the most utilised technologies thus far. The main reasons for their relevance are their long lifecycle, high power density and fast response. Li-ion and NiMH batteries may be considered as a valid alternative for on-board ESS when a high degree of autonomy is required. However, more advances in terms of durability and power density seem to be still needed for batteries to be extensively used. Flywheels made of composite materials offer interesting features for railway systems, but safety issues may limit their application to wayside ESSs. The combination of EDLCs and batteries has been identified as the most promising solution for on-board systems providing catenary-free operation.

Sending the excess regenerated energy back to the main distribution grid with reversible substations may be regarded as a very interesting alternative to reduce energy consumption in urban rail systems. The greatest advantage of this option is that the upstream AC network is permanently receptive and, as a result, all the regenerated energy may be potentially recovered. However, the economic benefits of reversible substation strongly depend on the possibility to sell the energy to the public network operators and the price set by them.

Finally, even though regenerative braking is a proven technology, its application in urban rail systems remains relatively unexploited.

Chapter 5-SYSTEMS APPROACH TO ENERGY OPTIMISATION OF URBAN RAIL SYSTEMS.

5.1. Introduction

Chapters 2 and 4 have addressed issues related to i) the characteristics of urban rail systems, ii) their favourable and unique features that make them suitable for effective energy optimisation, iii) their main energy flows (e.g. a Sankey diagram has been introduced illustrating main flows of power and energy consumption in a typical urban rail system) and iv) the technologies that can enhance the use of regenerative braking as a successful approach to energy conservation (e.g. on-board and stationary Energy storage systems). The literature analysis has also shown that the majority of recent advances to reduce energy consumption in railway systems have focused on the traction subsystem, primarily by using regenerative braking, applying energy-efficient driving strategies, or improving the propulsion chain efficiency (Powell *et al.*, 2014). This is also in line with the three approaches to energy optimisation in urban rail systems operation proposed by Oettich *et al.* (2004) i.e. driving style and timetable, regenerative braking and adapting supply to demand in a flexible way. It has been concluded that a systemic approach to energy usage of urban rail systems is currently lacking. This Chapter aims to define a systems approach to improve energy efficiency using combined technologies and strategies tailor-made for the particular system targeted, contributing to research objective 02 (RO_02, RQ_02). This includes a taxonomical approach assessing and categorising interventions based on technology (e.g. ESS) and/or strategies (e.g. eco-driving techniques) in section 5.2 as well as establishing a decision-making methodology in section 5.3 validated through expert consultation as described in Chapter 3. Finally section 5.4 will draw some chapter conclusions.

5.2. Taxonomy of energy efficiency measures for urban rail systems

5.2.1.Methodological aspects

As described in Chapter 3, the methodology used for the research presented in this chapter follows an inductive approach. The first step towards a whole-systems view of energy conservation in urban rail systems requires an appraisal and categorisation of the most promising technologies and strategies in the available body of research. To do so, a systematic literature assessment has been primarily conducted using international online databases e.g. Scopus[9] as well as the Newcastle University Library repository, which is linked to the major electronic resources worldwide. The main keywords used in this literature search are shown in Table 18.

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[9] http://www.scopus.com

Furthermore, relevant unpublished information from communications with urban rail operators, dedicated conferences, seminars and workshops were examined. In addition, as the topic is not only of academic interest, the literature search also included international databases of research and industrial projects e.g. the Transport Research Portal[10] and Spark[11]. In general, the literature assessment has been focused on the past 15 years, although older resources have also been consulted. In total, over 200 documents and websites have been reviewed for the purpose of this section.

Topic	Keyword used
Energy efficiency measures in general	Energy consum*, efficiency, reduc*, saving*; rail*; urban rail; metro; tram; light rail; technolog*; strateg*; operation*
Regenerative braking	Regenerative braking; energy recovery; timetable optimisation; energy storage; on-board, stationary, wayside, trackside system*; reversible, inverting, bidirectional substation*; supercapacitor*; ultracapacitor*; flywheel*; batter*
Energy-efficient driving	Energy efficient driving; eco-driving; speed profile*; coasting; Driving Advice System*; Automatic Train Regulation, Operation; traffic management optimisation
Energy-efficient traction system	Power supply line, network, grid; electrical loss*; traction; electrical motor*; permanent magnet; vehicle mass reduction; lightweight material*
Comfort functions	Temperature control; demand-controlled ventilation; heating; air-conditioning; thermal demand; lighting; optimal regulation, control; waste heat recovery; underground, subway station*, escalator*
Energy measurement and smart management	Energy metering, measurement, management; renewable power; smart grid*

* The use of asterisks at the end of words allows for different suffixes to be included in the search

Table 18. Summary of topics and associated keywords used in the systematic review of the literature

The operational and technological measures resulting from this assessment have been classified into five cluster groupings, namely i) regenerative braking, ii) energy-efficient driving; iii) traction efficiency, iv) comfort, v) measurement and management. Details on each of these groups are provided in the following subsections (5.2.2-5.2.6).

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[10] http://www.transport-research-portal.net
[11] http://www.sparkrail.org

5.2.2.Regenerative braking cluster

As discussed in Chapter 4, regenerative braking is regarded as one of the most promising solutions to optimise energy usage in electrified urban transport networks. The regenerated energy primarily feeds the on-board auxiliary functions, with the excess energy usually being returned into the supply line to power other vehicles accelerating in the same electric section. However, since the consumption of auxiliaries is relatively minor and the simultaneous acceleration and deceleration of different vehicles is unlikely to happen, a considerable amount of braking energy is still wasted into braking resistors. The following options are currently available to maximise the utilisation of the regenerated braking energy in urban rail: i) optimising the service timetables to increase the energy transfer between vehicles, ii) using trackside and/or on-board energy storage systems (ESSs) and iii) sending the regenerated energy back to the upstream AC network by means of reversible substations. These three aspects have been discussed extensively in Chapter 4, therefore only a brief summary is provided below.

Energy-optimised timetables

Synchronising accelerating and braking vehicles by means of timetable optimisation is a straightforward action to maximise the use of regenerated braking energy in urban rail. A few examples available in the literature show that significant energy savings of up to 14% can be achieved with this measure (Nasri *et al.*, 2010; Boizumeau *et al.*, 2011; Kim *et al.*, 2011; Peña-Alcaraz *et al.*, 2011). Additionally, timetable optimisation may limit peaks of power consumption, which represents an important issue in urban rail systems (Albrecht, 2004; Chen *et al.*, 2005). The optimum implementation of this operational measure requires a real time control system recalculating the schedule in case of unforeseen events or delays as well as advising drivers on best departure times and driving strategies. Its investment cost may be relatively low though, especially if compared to other technologies such as energy storage or reversible substations. Therefore, timetable optimisation should be considered as a primary option to increase the benefits of regenerative braking in urban rail.

Energy storage systems

ESSs were extensively discussed in Chapter 4 (see section 4.10 for conclusions). If properly dimensioned, both on-board and stationary ESSs may lead to i) Considerable traction energy savings in urban rail of typically between 15% and 30%; ii) contribution to stabilising the network voltage; iii) shaving power consumption peaks (Rufer *et al.*, 2004; Steiner and Scholten, 2004; Destraz *et al.*, 2007; Steiner *et al.*, 2007; Barrero *et al.*, 2008; Chymera *et al.*, 2008; Barrero *et al.*, 2010; Moskowitz and Cohuau, 2010; Domínguez *et al.*, 2011a; Lee *et al.*, 2011b;

Ciccarelli *et al.*, 2012; Iannuzzi *et al.*, 2012a; Iannuzzi and Tricoli, 2012; Teymourfar *et al.*, 2012; Iannuzzi *et al.*, 2013).

Reversible substations

Reversible substations were also discussed in Chapter 4 (see section 4.10 for conclusions). It has been estimated that this technology could reduce traction energy consumption by 7-11% in existing urban rail systems (Cornic, 2011; Ortega and Ibaiondo, 2011a; Warin *et al.*, 2011).

5.2.3. Energy-efficient driving cluster

This cluster comprises two main approaches: eco-driving techniques and optimised traffic management.

Eco-driving techniques

Eco-driving refers to the group of techniques intended to operate rail vehicles as efficiently as possible while ensuring the safety and punctuality of services. In addition to energy consumption reduction, eco-driving strategies have as added benefits contributing to the improvement of passenger comfort through smoother driving and reducing the wear of components (e.g. running gear). The basic principles of eco-driving can be described as i) optimising the speed profiles, ii) coasting and iii) using the track gradients for operational benefit.

To determine the traction energy consumption of rail services, acceleration profiles and maximum speed limits are critical factors to be considered. Hence, their optimisation (within the existing safety and operational restrictions) may lead to significant energy savings. For instance, a readjustment of the speed limits in the Brussels metro from 72 to 60 km/h and from 60 to 50 km/h was reported to result in traction energy savings of 15%, although an additional train was necessary to compensate for the slight increase in the journey time (Ticket to Kyoto project, 2011). Another interesting example is the Sao Paulo system where it has been reported that the most energy-efficient driving profile consisted in reducing the maximum speed at the expense of increasing the acceleration rates (Alves and Pires, 2010), which might seem counterintuitive.

As briefly referred to in Chapter 2 (see section 2.1), coasting is one of the basic modes that define single train movement (see Figure 6, p. 15). Coasting can be understood as "*an extended period of free running that makes up an operational phase in its own right*" (Powell and Palacín, 2015b). Different methodologies to determine the optimal coasting points and the associated speed profiles have been suggested in the literature e.g. Bocharnikov *et al.* (2007); Chuang *et al.* (2008); Miyatake and Ko (2010); Ding *et al.* (2011); Malavasi *et al.* (2011); Ke *et al.* (2012).

Despite the short distances between stations that characterise urban rail systems, applied studies have demonstrated that significant reductions in traction energy consumption are possible by coasting. For instance, energy savings of about 20% with an increase of 5% in the running time were reported for specific lines of London and Istanbul metro systems, respectively (Açikbaş and Söylemez, 2008; Hathway, 2012).

The effect of track gradients in both accelerating and decelerating phases is another important aspect to be considered in designing energy-efficient driving strategies for urban rail. For instance, in systems where stations are at a higher level than the track, the uphill gradient may help stop the rail vehicles with less braking effort, whereas downhill gradient may contribute to save energy during the acceleration phase (Hoang *et al.*, 1975; Duarte and Sotomayor, 1999).

The potential offered by the energy-efficient driving techniques just described may be exploited in large part by operational or simple technological measures. Thus, installing trackside information systems advising on optimal speeds and coasting points (Ke *et al.*, 2012) and training drivers in eco-driving techniques would lead to significant short-term traction savings with relatively low investment costs (Sandor *et al.*, 2011). It must be noted that for eco-driving training measures to be successful, keeping a high degree of awareness and motivation among the drivers is crucial.

Additionally, on-board Driving Advice Systems (DAS) are gaining increasing acceptance as a tool to save energy in urban rail operations. Based on pre-loaded algorithms and data defining each individual trip, these devices advise the driver on the best strategies to follow according to the running time and the train position (Wong and Ho, 2007; Jin and Kadhim, 2011). DAS allow for greater energy savings than just operational measures, but they necessarily imply refurbishment of current rolling stock. Generally, DAS systems can be categorised into the following three types: Timetable and generic info to driver via paper or screen (Type A), dynamic advice on how to drive the train efficiently to a predetermined timetable (Type B), optimising traffic flow by dynamically re-planning the timetable (Type C). Type A is the most commonly found in rail systems (Kent, 2009). Similarly, DAS can be connected to the control or traffic management centre, known as C-DAS or stand alone, also termed S-DAS i.e. cooperative or autonomous, both with various degrees (Palacín, 2012).

A further step towards more energy-efficient driving in urban rail is the implementation of Automatic Train Operation (ATO) systems, which allow for real time control of the optimum speed profile with no influence from the driver (Chang and Sim, 1997; Liu and Golovitcher, 2003; Ke and Chen, 2005; Domínguez *et al.*, 2011b). Both driverless and semi-automated operations are possible in ATO systems although its implementation in existing systems may face important barriers that are not always technical e.g. drivers' opposition (UIC, 2003).

Optimised traffic management

Eco-driving strategies generally imply an increase in the running time, so their successful application depends on the availability of time buffers. These typically are included in timetables as an allowance for impeded running of services. Optimising these recovery margins is therefore indispensable to save energy while ensuring service quality (Wong and Ho, 2007; Ding *et al.*, 2011).

Reducing platform dwell time may substantially increase the potential for energy-efficient driving. Furthermore, this measure may help improve passenger satisfaction, as it is generally preferred to have slightly longer running times between stations rather than longer platform dwell time. Aside from schedule reformulations, implementing explicit and accurate information systems in vehicles and stations may shorten both boarding and alighting times (UIC, 2003).

Automatic Train Regulation (ATR) systems, typically designed to ensure safety and punctuality in complex urban rail systems, can also be used for energy saving purposes. Thus, ATR may be linked to DAS so that coasting can be used to avoid conflicting movements as well as for station stops, hence minimising energy waste in stopping and restarting. A real-time traffic regulation from an energy efficiency point of view can be achieved by implementing optimisation algorithms such those proposed in Chang and Chung (2005); Sheu and Lin (2012).

5.2.4.Energy-efficient traction systems cluster

This cluster comprises three main areas, namely: i) reducing energy losses in the power supply network, ii) reducing losses in on-board traction equipment and iii) vehicle mass reduction.

Reducing losses in the power supply network

The resistive losses in the power distribution network are a quadratic function of the current. Therefore, they can be significantly reduced by limiting the power peaks caused by the simultaneous acceleration of different trains in the network. The optimisation of timetables and the use of regenerative braking technologies are key measures for this purpose, as previously discussed. Likewise, energy losses may be minimised by selecting higher electrification voltages, although this may imply excessively high investment costs in existing systems.

Another option to reduce energy losses in the power supply network is selecting low-resistance materials for the feeder lines. Despite requiring relatively high investment costs, an increasing number of third rail powered systems e.g. the

London Underground are replacing the standard steel conductor rails with aluminium-based ones offering up to 50% less resistance (Hartland, 2012). Superconducting cables may represent an alternative to conventional line conductors but, though promising, this technology is still in the research and development stage (Takagi, 2010; Tomita *et al.*, 2010).

Reducing losses in on-board traction equipment

Energy losses in on-board traction equipment are predominantly due to inefficiencies in the motors themselves, whereas losses in power converters and transmissions systems are relatively minor (see Chapter 2, section 2.2.1). Hence, the greatest improvements in traction efficiency can be achieved by using more efficient motors. In this regard, the Permanent Magnet Synchronous Motor (PMSM) represents a very promising alternative to the state-of-the-art asynchronous machines due to its very high efficiency of up to 97% (Kondo, 2010).

PMSMs use permanent magnets in the rotor instead of the conventional excitation current to generate the magnetic field, minimising electric losses. Additionally, their lower cooling requirements enable PMSMs to be mounted in totally enclosed configurations, allowing for lighter and more compact designs with less maintenance and lower noise emissions (Kondo *et al.*, 2008). Furthermore, the high torque offered by PMSMs makes a direct drive i.e. gearless configuration easier to implement, which can further reduce energy losses, mass and noise emissions (Germishuizen *et al.*, 2006; Peroutka *et al.*, 2010). A major drawback of synchronous motors is the need for dedicated inverters (Koerner and Binder, 2004; Uzel and Peroutka, 2010; Barcaro *et al.*, 2011), increasing investment costs. PMSM is a commercially available technology that has been successfully verified in urban rail applications. For instance, PMSMs have been tested in the Hankyu (Japan) commuter railway and Tokyo metro systems with reported traction energy savings of 9% and 12–13%, respectively (Kato, 2012).

Optimal management of the traction equipment according to the operating conditions may also lead to increases in traction efficiency of 1–5% (UIC, 2003; Sandor *et al.*, 2011). For instance, shutting off some of the traction groups instead of operating them all at partial load during coasting, cruising or standstill, may reduce energy losses in motors and converters. These are operational measures that essentially require an on-board traction software optimisation, meaning their implementation costs are relatively low.

Vehicle mass reduction

Lighter vehicles require lower mechanical resistance to advance and require less kinetic energy to reach the same level of performance. Therefore, minimising overall vehicle mass would reduce traction energy consumption. The ratio of the traction energy saving over the mass reduction is estimated to be about 0.6–0.8 for urban rail (Carruthers *et al.*, 2009; García Álvarez A and Martin Cañizares, 2012), although it may be slightly lower when using regenerative braking. Furthermore, reducing rolling stock weight results in less damage to the track and reduced wear of wheels and brakes, consequently lowering the operational and maintenance costs of the system (Eickhoff and Nowell, 2011).

An approach to reduce rolling stock mass is to introduce lightweight materials such as composites. Robinson and Carruthers (2006) identified that the proportion of a vehicle's tare mass that can be potentially influenced by material substitutions is around 80% including bodyshell, windows, exterior attachments, bogies, passenger interior, seats, driver's cab interior and cabinets, external doors and couplers. Some examples of mass reduction projects using lightweight materials in urban rail include the following: development of composite grab rails 50% lighter than existing stainless steel bars (Carruthers *et al.*, 2009); replacement of floor panels by 40% lighter sandwich constructions (Hudson *et al.*, 2010); development of a crashworthy driver's cab using advanced composite sandwich materials up to 40% lighter (Carruthers *et al.*, 2011); reducing the electric cabling throughout the vehicle (Robinson and Nomoto, 2006). These measures should be primarily implemented at design stages, although retrofitting may be also viable in some cases.

In addition to the use of lightweight materials, upgrading the traction equipment can reduce the overall mass of rail vehicles. For instance, the use of PMSMs, gearless drives and power converters based on new semiconductors (Railway Gazette, 2012b) may result in significant mass reductions. Furthermore, the use of mechatronics i.e. controlling the suspension and guidance functions electronically is likely to be implemented in future, lightweight rail vehicles (Goodall and Kortüm, 2002). Adjusting the train length according to passenger demand has also been reported as an obvious but interesting approach for saving energy through mass reduction, especially during off-peak periods (Gunselmann, 2005a; Anderson *et al.*, 2009).

5.2.5. Reducing the energy consumption of comfort functions cluster

This cluster comprises the following three main areas: i) rolling stock related measures for service mode, ii) rolling stock related measures for parked mode and iii) infrastructure related measures.

Rolling stock related measures for service mode

Heating, ventilation and air conditioning (HVAC) demand in rail vehicles can be reduced by minimising heat transfer with the outside environment, which primarily requires improving the thermal insulation of vehicles' walls, doors, windows, floor and ceiling. Furthermore, the use of smart windows automatically adjusting their opacity according to the sunlight intensity can significantly reduce the cooling demand, particularly in surface-level services (Baetens *et al.*, 2010). These measures are generally more suitable for new vehicle designs, although they may be also considered in retrofitting to some extent.

Additionally, an optimal control of the fresh air supply can significantly reduce the HVAC demand. Thus, demand-controlled ventilation based on the concentration of CO_2 i.e. according to the actual human occupation levels of the vehicle guarantees that no energy is wasted in conditioning unnecessary fresh air intakes (Chow and Yu, 2000; Chow, 2002; Kokken, 2003), translating into reported energy savings of up to 55% (Amri *et al.*, 2011). In this sense, reducing avoidable door openings may also play an important role (Kwon *et al.*, 2010). Another advantage of smart control of ventilation is the so-called ''free-cooling'', which essentially involves lowering the indoor temperature by introducing greater amounts of outside air.

Alternatively, the thermal demand in rail vehicles can be minimised by optimally adjusting the comfort temperatures (Li and Sun, 2013). Thus, a slight decrease in the target indoor temperature in the heating mode or a slight increase in the cooling mode may yield substantial energy savings without affecting passenger satisfaction. This sort of adjustment may provide the additional benefit of improving passenger comfort in many cases.

Improving HVAC systems efficiency generally requires upgrading the existing equipment. Thus, the use of heat pumps may lead to important energy savings in heating as they can perform between twice and four times more efficiently than common electrical resistors. This technology is particularly suitable for applications where the ambient temperatures are normally above 5 to 7° C e.g. in tunnel environments (Amaya J, 2009). Moreover, heat pumps have the capability to work as air-conditioning machines when cooling is required, avoiding the duplication of equipment and consequently allowing for weight savings. An optimal regulation of their capacity according to demand, for instance by means of variable frequency compressors, would notably increase the performance of heat pumps in both cooling and heating modes (Amaya J, 2009; Kumar and Kar, 2010). As an alternative to heat pumps, air-cycle refrigeration systems have been proposed for air-conditioning functions mainly because of their high reliability and the absence of environment-harmful refrigerants; however, their coefficient of performance is approximately half that of heat pumps (Ampofo *et al.*, 2004c; Wang and Yuan, 2007).

The recovery of waste heat produced by the traction equipment might also be regarded as an alternative to reduce the energy consumption of HVAC systems. This energy could be directly used for heating purposes (UIC, 2003), for driving absorption cooling machines (Javani *et al.*, 2012), or for generation of electric power on-board (Chen *et al.*, 2010a). This would also reduce the thermal loads in tunnels and, consequently, the air-conditioning demand inside the vehicles. However, the dispersion of the heat sources and their relatively lower temperature hinder the application of these innovative concepts in urban rail.

Another area that can be targeted to optimise energy consumption in vehicles while in service is lighting, which may be notably reduced by using efficient light-emitting diodes (LEDs). This technology has been widely proved in household applications (Han *et al.*, 2010) and its usage in rail vehicles is gaining increasing attention (Railway Gazette, 2010a). Furthermore, the use of more efficient lighting contributes reducing the air-conditioning demand in vehicles (Ampofo *et al.*, 2004b).

Rolling stock related measures for parked mode

Several of the technological measures discussed above can clearly reduce the energy consumption of comfort functions during standstill. However, the greatest energy saving potential in parked mode seems to lie in optimising the setup and control of the comfort functions (Gunselmann, 2005a). Thus, redefining the threshold temperatures during hibernation and maintenance operations, alongside the implementation of automatic control systems for heating and lighting, may reduce the energy consumption in parked mode by up to 50% (UIC, 2003).

Infrastructure related measures

Cooling the tunnel environment can significantly reduce the HVAC demand in subway stations as well as in rolling stock itself (Ampofo *et al.*, 2004c; Thompson *et al.*, 2006). In this regard, maximising the natural ventilation is a key solution as it permits the evacuation of heat gains with no energy consumption (Lin *et al.*, 2008; Kim and Kim, 2009; Raines, 2009; Huang *et al.*, 2010; Huang *et al.*, 2011). To achieve this, it is important that stations and tunnels are designed with adequate ventilation shafts, as it is normally problematic to build them into existing systems. Other non-conventional, energy-efficient options to minimise the thermal loads at infrastructure level are: i) using heat pipes to enhance the capacity of the surrounding soil to absorb heat from the tunnel environment (Thompson *et al.*, 2007); ii) using groundwater as a direct cooling source (Maidment and Missenden, 2002;

Ampofo *et al.*, 2011); iii) using phase-change materials (PCMs) to absorb heat from tunnels during operational hours while releasing it at night (Thompson *et al.*, 2006).

Additionally, the use of platform screen doors may prevent the heat transfer from the tunnel to the station, although their use may considerably increase the ventilation demand in tunnels (Hu and Lee, 2004). Furthermore, some authors have expressed concern about their effect on passenger evacuation during emergencies e.g. (Qu and Chow, 2012).

In order to enhance the performance of conventional heat pump systems providing heating and/or cooling in stations, geothermal technology appears to be a very promising option (Kuo and Liao, 2012; Yuan, 2013). The higher performance offered by geothermal heat pumps lies in the fact that they interchange heat with underground sources i.e. soil or groundwater, whose temperature is much more constant than air temperature throughout the year. Moreover, geothermal systems consume no water in cooling towers, which is a very important advantage in hot climates where this is a scant source. However, they require higher investment and their feasibility depends on the availability of proper underground sources (Self *et al.*, 2013).

If possible and feasible, the use of solar thermal energy is also an interesting way to reduce the consumption of HVAC systems in stations. Thus, it can be used directly for heating purposes (Cui *et al.*, 2010) or to power absorption cooling machines (González-Gil *et al.*, 2011; Eicker *et al.*, 2012). However, the potential of this alternative has not been entirely exploited in railway systems so far.

The implementation of dynamic control strategies may lead to large energy savings in HVAC and significant improvements in comfort with relatively small investments (Fong *et al.*, 2006). Hence, understanding and predicting passenger flows, air circulation and temperature distribution are key factors to achieve optimal operation of HVAC systems in stations (Ke *et al.*, 2002; Fukuyo, 2006; Yuan and You, 2007; El-Bialy and Khalil, 2011).

Regarding energy consumption in lighting, the introduction of more efficient lamps may account for significant energy savings. For instance, energy savings of 32% and 40% were achieved in Bielefeld (Germany) and Hong Kong underground stations, respectively, by replacing the existing lighting equipment with fluorescent and LED lamps (Anderson *et al.*, 2009; Ticket to Kyoto project, 2011). Also, an optimal adjustment of lighting intensity to passenger demand e.g. automatically switching off the station lighting during no operation times may lead to noticeable energy savings (Hayashiya *et al.*, 2012).

Escalators, lifts and other passenger conveyor systems are components of the infrastructure subject to energy optimisation. The greatest energy efficiency improvements for such systems lie in the optimization of their number and allocation (at design phases) and in the implementation of a demand-based control. In this sense, understanding passenger behaviour is of vital importance (Ma *et al.*, 2009; Zhang and Han, 2011; Zhu *et al.*, 2011).

Finally, energy savings in stations can be maximised through integrated management of all their subsystems. As a consequence, reductions of 5–10% in the energy consumption of underground stations may be expected when collectively applying adaptive control strategies to HVAC, lighting and passenger conveyor systems (Fuertes *et al.*, 2012; Giretti *et al.*, 2012).

5.2.6. Energy measurement and smart management cluster

This cluster comprises energy metering, local renewable power generation and smart power management as key actions for achieving greater energy savings in urban rail systems.

Energy metering

While using automated metering systems to collect energy consumption data in vehicles and other urban rail subsystems is not an energy efficiency measure by itself, it is indeed a valuable tool for optimising energy usage within the system. Furthermore, a good understanding of energy flows is paramount to identify areas with greater energy saving potential and to monitor the effects of the implemented measures (Stewart *et al.*, 2011; Evans, 2012). In addition, the information provided by energy meters is essential for energy billing purposes, an issue with growing relevance in liberalised railway markets (Størmer, 2012). Allowing private operators to pay for real energy consumption, rather than using average estimations, may represent a major incentive for them to apply energy efficiency measures. In this regard, the standardisation of metering equipment and procedures is a key matter to be addressed (CENELEC, 2007; UIC, 2009; Gatti and Ghelardini, 2011).

Micro-generation of renewable power within the system

Depending on the characteristics of the system and on the availability of renewable energy sources in the area, the local generation of electricity may be an interesting solution to reduce power consumption from the public network. For instance, photovoltaic solar panels may be installed in stations and depots to partially meet their own demands (Faranda and Leva, 2007; de Wilde d'Estmael *et al.*, 2013). Similarly, solar panels could be installed along the track helping to feed the signalling systems and the substations auxiliaries (Vrignaud, 2011). Furthermore, roof-mounted solar panels on vehicles could provide enough power to supply their auxiliary systems (Vorobiev and Vorobiev, 2011), although these would introduce additional weight which is regarded as a serious concern. This hurdle might be overcome yet by suggesting the use of flexible, light panels based on polymer solar cells (Railway Gazette, 2010b; Li *et al.*, 2012a). Interestingly, using wind turbines in depots, stations or along the track has been proposed as an alternative or a complement to solar power systems (Anderson *et al.*, 2009; de Wilde d'Estmael *et al.*, 2013). Regardless of the kind of energy source, optimal integration of renewable power generation in railway systems will typically require the use of ESSs alongside dedicated power management controls, which may compromise the economic viability of these measures.

Smart energy management

The foreseeable increase in the use of both regenerative braking and renewable energy generation in urban rail systems will result in the need for optimised management of energy flows within the network. In this regard, the application of the smart grid concept is gaining growing attention. This concept was primarily developed for electric networks with distributed power generation (Barsali *et al.*, 2011; Chéron *et al.*, 2011; Díez *et al.*, 2012). This approach enables efficient management of all the energy sources in the network according to actual demand. This means, for instance, that the power from renewable sources, from regenerative braking or from the public grid can be either used to instantly meet the power demand of the system, or stored for later use shaving peak consumptions, which may account for important cost savings. Applying the smart grid concept requires the development of an automatic control of voltage distribution within the network (Brenna *et al.*, 2013). This alone often fails to be economically viable (Hayashiya *et al.*, 2012), although selling the energy back to the grid could help reduce its payback period. As a pioneering attempt to integrate smart grids into urban rail systems, it is worth mentioning the energy optimisation project launched by SEPTA in Pennsylvania (USA) (Poulin *et al.*, 2012).

Furthermore, the integration of urban rail networks with other energy independent systems in their vicinity such as buildings, other urban mobility systems or renewable power generation plants, has been proposed as an extension of the smart grid concept for a ‘‘smart city'' energy management (Falvo and Martirano, 2011; Brenna *et al.*, 2012). For instance, it has been suggested that the excess regenerative braking energy from metro systems could help powering an urban network of electric vehicles (Falvo *et al.*, 2011). Likewise, the heat from large underground systems could be used for heating purposes in buildings close to stations or to ventilation shafts (Le Clech, 2005; Gilbey *et al.*, 2011). Additionally, it has also been suggested that the power generated in nearby renewable energy plants could be used to feed the urban rail system itself, consequently reducing its environmental impact and improving its social acceptability (Anderson *et al.*, 2009; Transport for Geater Manchester, 2011).

5.2.7.Clusters holistic assessment

The five clusters of non-exclusive operational and technological measures to optimise energy usage in urban rail systems i.e. i) regenerative braking, ii) energy-efficient driving; iii) traction efficiency, iv) comfort, v) measurement and management, have been organised as part of this thesis not only by type of measure i.e. operational or technological but also according to the level of application i.e. whether they are applicable to rolling stock, infrastructure or the system as a whole. Operational measures aim at using both existing rolling stock and infrastructure more efficiently, which can be achieved with minor changes to the facilities. In contrast, the introduction of new technologies requires higher investment costs and implies major modifications to the system equipment. The outcome of this multi-layered systemic taxonomical approach is illustrated in Figure 23.

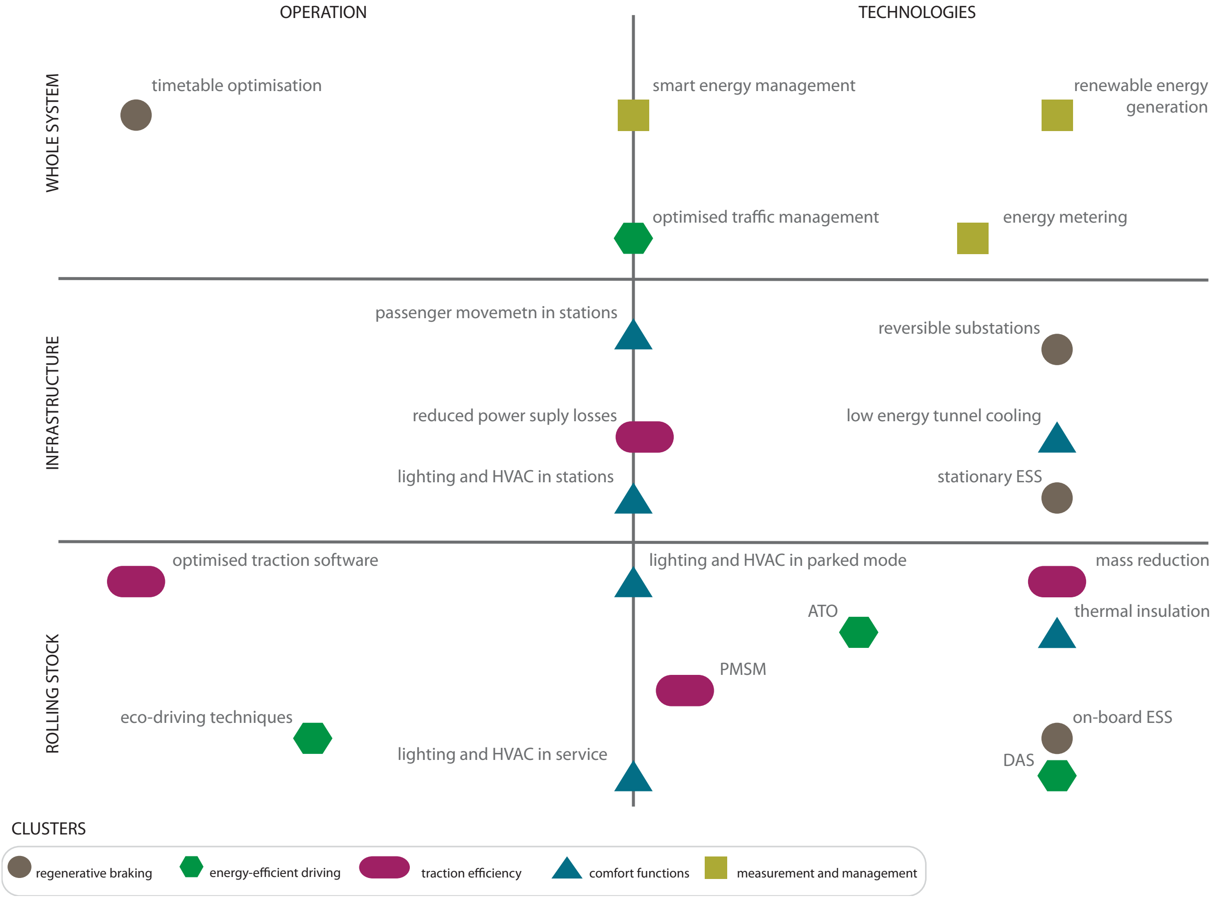

Figure 23. Main measures and actions for energy efficiency classified by cluster, type and implementation area

5.3. Systems dimension of energy optimisation measures

5.3.1.Methodological aspects

The previous section has described a range of energy saving measures suitable for application to urban rail systems. These have also been grouped into distinct clusters providing a classification of such measures. In order to understand the systems implications of using different combinations of these clustered measures a systemic assessment is required. This section exemplifies this assessment and rating of energy efficiency measures for urban rail following an inductive approach (see Chapter 3). This includes a general analysis of the interdependences between the main measures described in Section 5.2, alongside a qualitative assessment of their individual potential energy savings, investment costs and technical suitability for current systems.

5.3.2.Interdependencies between energy efficiency measures

Most energy efficiency measures for urban rail systems are strongly interdependent, a characteristic highly related to complex systems. As such, a combination of measures may lead to higher or lower potential benefit than if applied separately, depending on their compatibility. Therefore, when evaluating a group of solutions, their benefits cannot be assessed individually, but the interactions between them must be considered. This calls for a systems-approach that analyses the interdependencies between these measures to understand the effects at whole system level. This approach is in line with Jackson (2003) who stressed the problem of sub-optimisation by concentrating on the performance of one part that could have detrimental effects elsewhere in the system (see Chapter 3).

The outcome of this holistic assessment research carried out is portrayed in Figure 24, showing a graphical representation of the interdependences between, and also within, four clusters of energy efficiency measures and technologies described in Section 5.2. The fifth cluster *energy measurement and smart management* is considered to be at a horizontal level acting as an envelope or umbrella and therefore not interacting with the other four at an individual level, but rather contributing equally to their success. For instance, through measures included in this fifth cluster such as continuous monitoring of the implemented energy efficiency technologies and procedures and smart management of system-wide energy flows, a more assured and confident approach to urban rail energy efficiency can be achieved. There are two different types of arrows in this figure, illustrating whether the interdependence between any two measures or clusters is positive or negative.

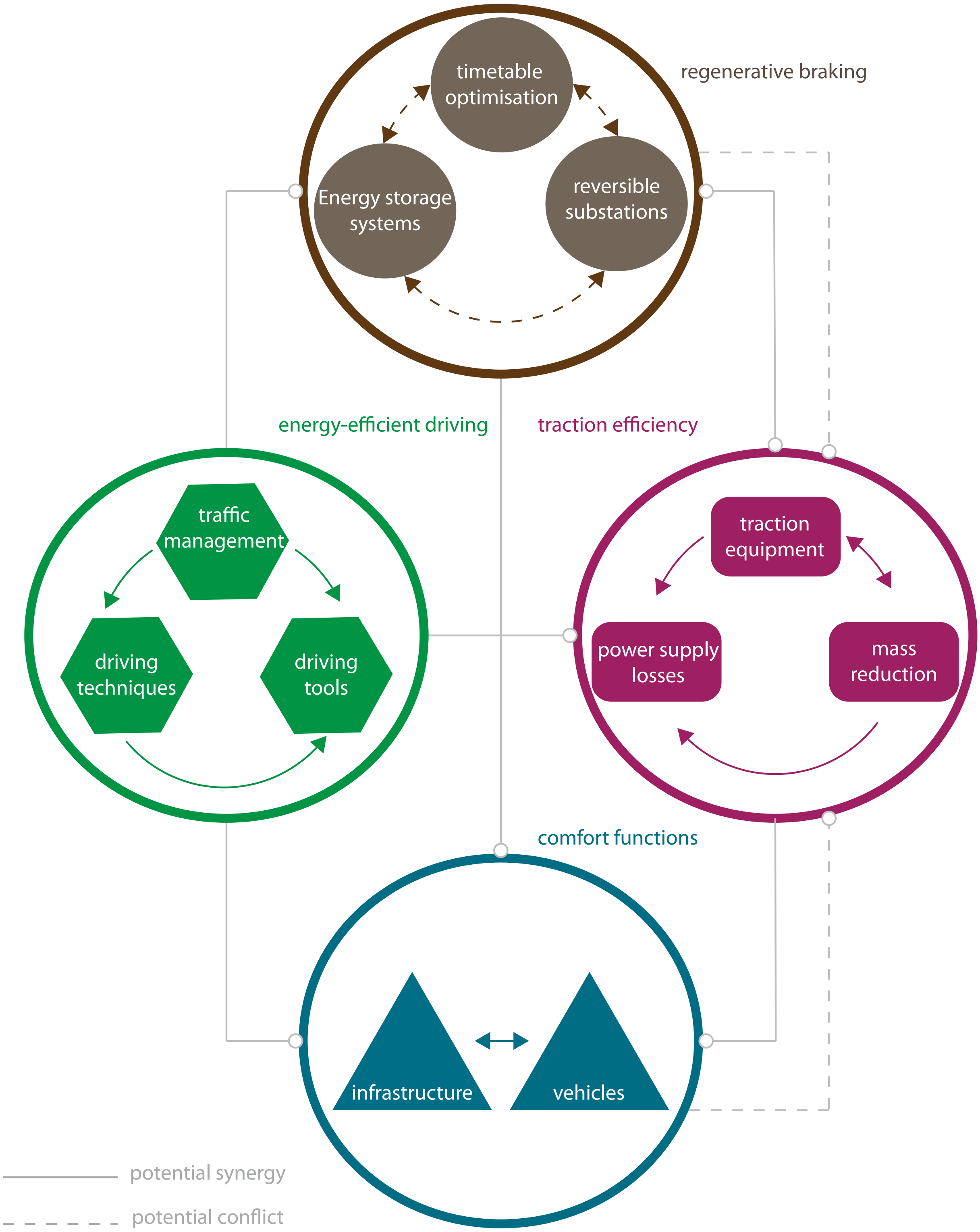

Figure 24. Graphical representation of interdependencies found between energy efficiency measures & clusters

The benefit of combining regenerative braking measures may be lower than the sum of the potential of each solution. For instance, the higher the regenerated energy transferred between trains is, the lower the potential for energy recovery through ESSs and substations will be, and vice versa. However, the combination of all three options may be needed to use the whole braking energy potential. Therefore the implementation of regenerative braking measures would require a complex optimisation assessment to obtain the greatest energy savings with the lowest investment cost. The interdependences of these technologies with other energy efficiency solutions have been found to be i) they may reduce consumption in comfort functions both at infrastructure and vehicle level as they avoid the dissipation of braking energy in tunnels and stations; ii) they minimise the losses in the supply network since they reduce power peaks in the line; iii) they may reduce vehicle mass as they minimise the need for on-board braking resistors; however, if on-board ESSs are used, the additional weight may increase the traction energy consumption.

An improved traffic flow control facilitates applying energy-efficient driving strategies. However, before implementing driving advice tools, a careful analysis should be carried out determining the most suitable driving techniques and optimal traffic control strategies needed. In general, eco-driving measures minimise resistive losses in the power supply line as they contribute to reduce current flow in the network. In addition, they may lower the thermal load in tunnels and stations due to their ability to reduce the intensity of the braking processes. Interestingly, the use of efficient traffic control systems may facilitate better interchange of braking energy between vehicles. Moreover, deceleration profiles that match the characteristics of the traction motors will lead to fewer losses in braking energy recovery.

Synergies must be expected from the combination of measures aimed at reducing energy consumption of comfort functions in vehicles and stations i.e. reducing the thermal load in tunnels and stations will lower the cooling demand in vehicles, and vice versa. In turn, measures such as upgrading the HVAC systems of vehicles e.g. heat pumps may increase rolling stock mass and, therefore, the traction energy consumption.

Actions to increase energy efficiency of the traction system are fully interconnected to each other, as shown in Figure 24. Thus, reducing traction energy consumption through enhanced drives leads to less resistive losses in the line. Moreover, improvements in traction equipment will generally imply mass reduction resulting in reduced traction consumptions and fewer losses in the line. Furthermore, minimising the losses of traction equipment enhances the braking energy regeneration reducing the thermal load in both tunnels and stations.

5.3.3. Assessment and rating of energy efficiency measures

The measures discussed in section 5.2 have been analysed to also obtain indicative values of their optimisation potential, rate their suitability for deployment on existing systems and gauge their potential cost implications. Table 19 summarises these results.

The range of values included in this table have been obtained by applying the average figures found in the literature (section 5.2) to a representative urban rail system with a typical energy usage ratio of 80:20 between traction and non-traction consumption based on the energy flows described in Chapter 2 and included in the Sankey diagram illustrated in Figure 8. These values are indicative and should be considered as an estimation of the potential order of magnitude of each of the measures.

The research has also assessed the suitability for deployment of the analysed measures for implementation in existing urban rail systems. This indicator of technical viability is comparatively rated as low, medium and high, depending on implementation barriers found. For instance, infrastructure-related measures that imply major modifications to the system would normally be regarded as less adequate solutions than less disruptive actions. Likewise, measures requiring the introduction of heavy and bulky systems in existing vehicles, e.g. on-board ESSs or heat pumps, are likely to be discarded due to integration and weight issues.

The analysis performed also gives a qualitative, comparative estimation of the investment cost for each measure. This assessment aims to enable a quick contrast between measures and is not intended to be an accurate valuation of their implementation cost.

Measures			Energy saving potential (%)[12]	Suitability for existing systems	Investment costs
Cluster	Category	Solution			
Regenerative braking	Timetable optimisation		1-10%	High	Low
	ESS	On-board	5-25%	Medium	High
		Stationary	5-25%	High	High
	Reversible substations		5-20%	High	High
Energy efficient driving	Eco-driving techniques	Coasting, optimised seep profile, use of track gradients	5-10%	High	Low
	Eco-driving tools	DAS	5-15%	High	Medium
		ATO	5-15%	Medium	High
Traction efficiency	Power supply network	Higher line voltage	1-5%	Low	High
	Traction equipment	Lower resistance conductors	1-5%	Low	High
		PMSM	5-10%	High	High
		Software optimisation	1-5%	High	Low
	Mass reduction	Materials substitution	1-10%	High	Medium

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[12] Estimated energy savings at system level for a standard case application

Comfort functions	Vehicles	Thermal insulation	1-5%	High	Medium
		Heat pump	1-5%	Medium	Medium
		LEDs	1-5%	High	Medium
		HVAC and lighting control in service	1-5%	High	Low
		HVAC and lighting control in parked mode	1-5%	High	Low
	Infrastructure	Low energy tunnel cooling	1-5%	Low	High
		Geothermal heat pumps	1-5%	Medium	Medium
		Control of HVAC, lighting and passenger conveyor systems	1-5%	High	Low
		LEDs	1-5%	High	Medium

Table 19. Evaluation of energy efficiency measures in urban rail system

Considering only measures rated as highly suitable for existing systems in Table 19, their individual energy saving potential can be plotted against their relative implementation cost, as shown in Figure 25.

Figure 25. Comparison of key measures based on energy saving potential and investment cost

A logical approach to interpret this comparison would be to focus on the low-medium and medium-medium quadrants representing the investment versus energy saving potential. Nevertheless, it is conceivable that given the interdependencies between measures, certain combinations that a priori might not seem promising (e.g. low-low combined with medium-low quadrant) could aggregate to savings bigger that the sum of their predicted individual energy saving potential. Moreover, given the different levels of technology maturity and market penetration of certain technologies (e.g. reversible substations, ESSs) these clusters could in the future change relative location within the plot area. For instance, the rapid development of battery technology over time and the increasing manufacturing volume driven by demand from different applications (e.g. Automotive) as well as novel applications (e.g. second life batteries) could see Stationary ESS move from the top right quadrant (high-high) to a medium investment cost quadrant while retaining its energy saving potential. Crucially, the interpretation of this comparison and the relative location of the different measures on the plot will be exacerbated by the intrinsic unique characteristics of any given urban rail system (e.g. topography, climatic conditions, timetable). Therefore it is essential that when applying this plot-based approach, a calibration process is undertaking to consider these issues (e.g. system characteristics).

Nevertheless, as an illustration and taking into account the interdependences between these measures, the most promising solutions for existing systems can be considered to be as follows:

- Improving control of comfort functions (lighting and HVAC), both in service and in stations;
- Applying eco-driving techniques and introducing driver advisory systems (DAS);
- Optimising the timetable to maximise the interchange of regenerative braking energy between vehicles;
- Installing stationary ESSs for recovering and reusing surplus regenerated energy;

Considering a hypothetical urban rail system with the typical energy consumption share of 80:20 between traction and non-traction applications as described previously, and where no energy efficiency schemes have been implemented yet, the combination of these measures can be estimated to lead to energy consumption reductions at system level ranging between 5 and 30% with a relatively short payback period. These savings include 0.8-17% from regenerative measures, 4-12% from eco-driving and 0.2-1% from comfort functions improvement. These figures have been obtained by applying the 80:20 ratio to the energy saving potential for each measure as described in Table 19 before selecting the resulting min-max percentage range per cluster. The overall estimated energy reduction at system level has been calculated by combining the effects of all clusters. This estimated energy saving benefit is just an illustration of the potential of combining technical and operational measures and is subject to calibration. As discussed above, the intrinsic interdependencies between measures and the critical influence of the unique characteristics of each individual urban rail system suggest caution when generalising figures. Table 20 provides a summary of this estimate calculation.

		Application				
Cluster	Measure	Estimated energy saving potential (%)	Traction (0.8 coefficient)	Non-traction (0.2 coefficient)	Combined estimated saving per cluster (%)	Estimated total combined impact (%)
Regenerative	Timetable optimisation	1-10%	0.8-8%	-	0.8-17%	
	Stationary ESS	5-25%	3.2-16%	0.2-1%		
Eco-driving	Eco-driving techniques	5-10%	4-8%	-	4-12%	
	DAS	5-15%	4-12%	-		
Comfort	HVAC & lighting in service	1-5%	-	0.2-1%	0.2-1%	
	HVAC & lighting in parked mode	1-5%	-	0.2-1%		
	HVAC & lighting in stations	1-5%	-	0.2-1%		
Estimated total combined impact (%)						5-30%

Table 20. Summary of estimate calculation of potential benefits of applying a selection of measures to a typical urban rail system

5.4. Development of a methodology for optimal implementation of energy efficiency measures in urban rail systems

The range of measures described in section 5.2 and analysed in section 5.3 can be considered as effective avenues to minimise energy consumption of urban rail systems. However it is neither realistic nor effective to apply them all in conjunction to a particular system, as discussed in the interdependencies subsection (5.3.2). This is especially true for existing systems, where restrictions for their application are greater. Therefore, an effective methodology is needed when defining and implementing a program of measures and interventions aimed at reducing the energy consumption of urban rail systems, improving their energetic efficiency and contributing to the overall system-wide energy conservation.

This methodology has been developed using a predominantly inductive approach enquiring about the suitability of current practice but perhaps more importantly applying systems analysis typical of hard systems positions known as Type A (Jackson, 2003) as described in Section 3.4 and illustrated in Figure 15.

The first step taken involved the identification of the existence of a problem in a social-technical system as urban railways, in this case, the need to enhance energy conservation rates through reducing the efficiency gap and optimising usage. This formulation phase allowed the identification of key areas of improvement.

The second phase of this methodology development requires identifying, defining and screening the potential alternatives based on the energy flows described (Chapter 2) and the technologies and measures (Chapter 3) addressing the key areas included in the formulation phase. This approach allows for pre-selecting combinations of technologies and strategies with interdependencies that enhance the achievement of the goal set. This phase would also require that the operator or stakeholder applies assessment tools i.e. models to assess the success likelihood of preselected measures.

The third and final phase involves an evaluation process comparing and ranking the alternatives leading to the decision and implementation of chosen interventions as well as the evaluation of the outcome.

The result of this approach is a systematic procedure to reduce energy consumption in urban rail, which fundamentally consists of the steps shown in Figure 26. Although this methodology has been primarily developed for application to existing systems, it can also be used in brand-new ones.

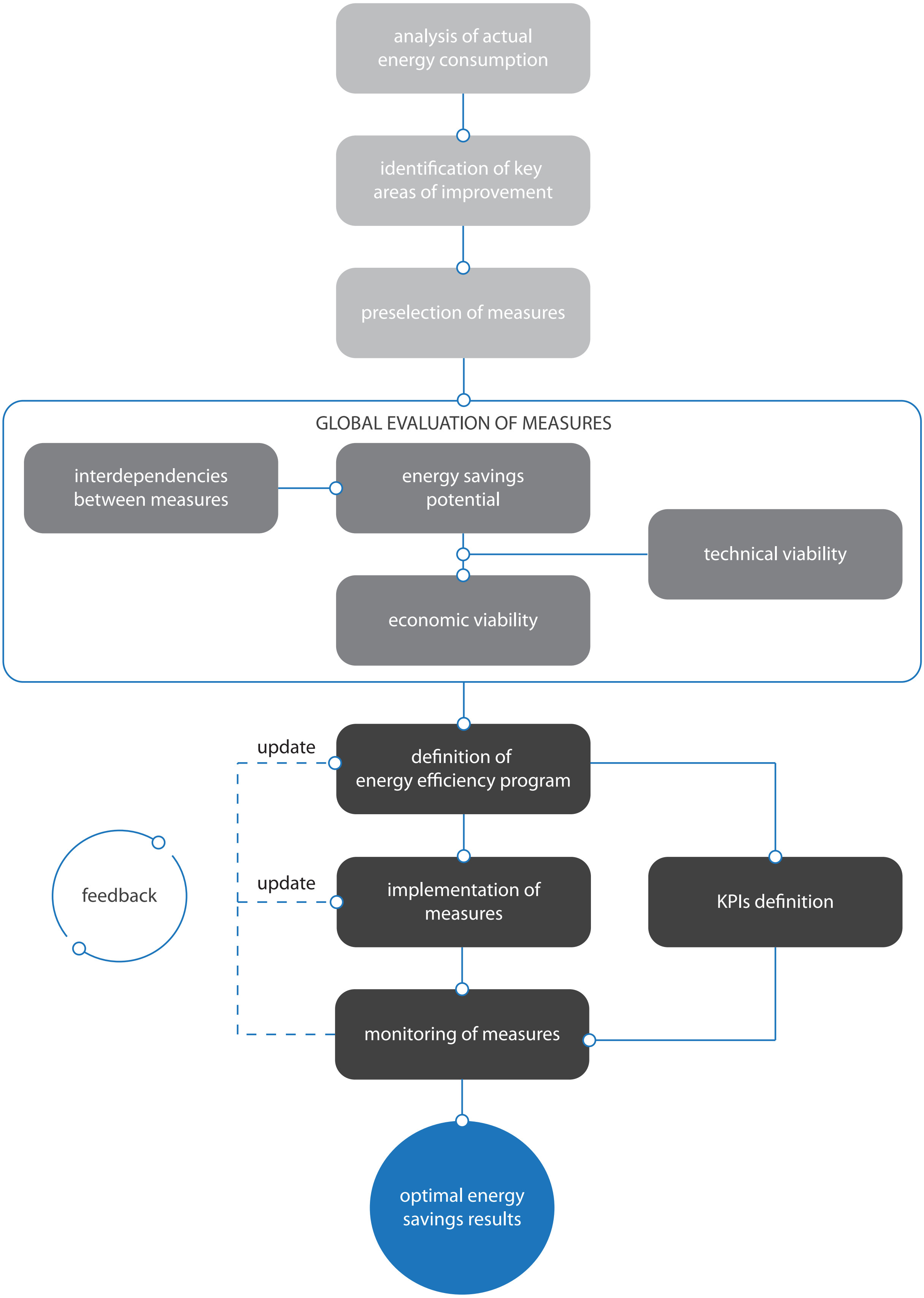

Figure 26. Systemic methodology for successful implementation of energy efficiency measures in urban rail systems

As seen in this diagram, analysing the actual energy consumption of the system in question should be the starting point of any energy efficiency programme. Thus, an accurate understanding of the energy flows within the system will enable identification of the areas with greatest potential for improvement, and to preselect a set of suitable measures accordingly. Based on these, preliminary solutions must be globally evaluated in order to prioritise their possible implementation. The principal criteria to be considered in this evaluation process includes the following key aspects:

1. The energy saving potential of the solutions. This has to be assessed from a systems perspective taking into account the synergies and conflicts that may emerge between the measures;
2. Their technical suitability for the system in question e.g. depending on whether the system is underground or surface operated, some measures may be considered impractical;
3. Their economic viability, which is influenced by their potential energy savings at systems level and by their technical suitability, among other economic factors concerning different stakeholders that will not be considered herein.

The solutions judged as the most promising after the evaluation process have to be fully defined in an implementation programme, which should also include a set of key performance indicators (KPIs) to monitor their real effect and contribution to energy conservation goals. The comparison between the expected and the actual energy savings will allow readjusting the original programme so as to obtain optimal results.

This methodology was refined and validated using a consultation with experts in the form of structured group interviews[13] (more details of this process are in Chapter 6).

5.5. Chapter conclusions

This chapter has given a comprehensive description of the systems dimension of energy usage in urban railway, addressing the second research question (RQ_02) as part of the second research objective (R0_02) of this thesis seeking to explore the suitability of current practice as part of developing a holistic monitoring framework. Specifically, this chapter has given an insightful overview on the potential of urban rail systems to reduce their energy consumption. Firstly, a comprehensive assessment of the main practices, strategies and technologies available to reduce urban rail energy consumption has been presented. This has led to classification of such measures into five different clusters that form the basis of an analysis of their potential to contribute to energy conservation objectives and an order of magnitude assessment of the trade-offs e.g. investment cost. Following this,

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[13] These group interviews were performed as part of research grant FP7-284868 and included operators from cities in France, Italy and Turkey, equipment manufacturers, academic experts and industrial associations.

the key points of a clear, logical methodology for optimal implementation of energy efficiency measures in urban rail have been discussed and the methodology has been presented. The main conclusions that can be drawn from the chapter are summarised below.

There are a broad range of energy efficiency measures that have proven to be successful in minimising the energy consumption of different urban rail subsystems, such as traction drives, vehicle comfort functions or stations. However, when considering their application, their potential energy savings should not be seen individually, but at system level. A good understanding of the subsystems' interactions is vital for an effective implementation of any energy efficiency programme. Furthermore, a continuous monitoring of energy consumption is a key aspect for the definition and tracking of such programmes.

For existing urban rail systems, the implementation of operational measures is normally preferred to the introduction of new technologies, as significant energy savings may be achieved with relatively low investment costs and minor modifications. Thus, enhancing the control of the vehicle comfort functions, optimising service timetables from an energy-saving point of view, or applying eco-driving techniques have been identified as the most promising solutions for those systems. Additionally, the use of stationary ESSs may maximise the use of regenerative braking energy with relatively low payback periods. The implementation of these four measures all together might realistically lead to energy consumption reductions of about 5-30% in standard existing systems without previous energy efficiency schemes.

This chapter contributes to existing knowledge by providing a comprehensive overview and assessment on how energy is managed in urban rail systems, the most promising actions to minimise its use and an estimate of the scale of potential savings. In addition, it describes a suitable step-by-step methodology for making decisions on implementation of measures. It can therefore prove useful as a reference for all stakeholders involved in addressing urban rail energy consumption. Nevertheless, since this investigation has highlighted the significant variability between different systems, its conclusions should be regarded as guidelines, with the evaluation of individual systems requiring a specific, in-depth analysis. The use of a complete framework that includes monitoring aspects (e.g. KPIs) appears essential to act as a key aid on such an in-depth analysis process.

Chapter 6-SYSTEMIC MONITORING FRAMEWORK

6.1. Introduction

Phase 1 of this research described in Chapters 2 and 4 explored in detail energy usage aspects of urban rail systems and existing measures (technologies and strategies) respectively addressing the first research objective (R0_01) and associated research question (RQ_01). A key outcome of this Phase 1 is the identification of typical energy flows within urban rail systems, as illustrated in the Sankey diagram included in Chapter 2 (Figure 8, p. 20), identifying the braking process as the most promising area for energy optimisation. Chapter 4 details the merits of using regenerative braking to address energy efficiency aspects at system level, assessing technologies and strategies for optimal management and deployment of regenerative braking interventions.

Similarly, Chapter 5 (Phase 2) has investigated in depth the interdependencies between measures to develop a holistic methodology to assess them addressing research question 02 (RQ_02) as part of the second research objective of this thesis (RO_02). The holistic methodology identifies the use of key performance indicators as a core instrument to successfully implement measures aimed at improving energy conservation. This Chapter 6 integrates these results as part of Phase 3 of this thesis to define an adaptable systemic monitoring framework architecture based on a hierarchical set of thermodynamic and physical-thermodynamic (see section 02.3) key energy performance indicators (KPIs), performance indicators (PIs) and parameters (Ps) all of which have been collectively termed key energy performance indicators (KEPIs). 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: i) a multilevel analysis of the actual energy performance of the system; ii) an assessment of potential energy saving strategies and iii) the monitoring of the results of implemented measures.

As discussed in sections 2.3 and 2.4 the use of indicators in rail systems, and particularly in urban ones, is limited with sporadic evidence in the literature. Most of the indicators used are at a subsystem level e.g. stations with rare if non-existent rail-related energy indicators. The only rigorous attempt to identify energy performance indicators in railway systems has been developed within the RailEnergy project (RailEnergy, 2011; Sandor *et al.*, 2011). This approach consisted of seven indicators measuring the overall energy consumption of the system, the energy consumption share for stabled 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 (Xu *et al.*, 2012), district heating networks (Pacot and Reiter, 2011) or industrial processes (Szíjjarto *et al.*, 2012). Therefore, this chapter applies a holistic approach in order to develop a comprehensive set of indicators for assessing and optimising energy consumption in urban rail systems, i.e. a set of KEPIs facilitating the process described in Figure 1 (p. 5).

Specifically, section 6.2 describes the methodological aspects of this research based on the structure described in Chapter 3, including a detailed overview description of the consultation process followed in the development and validation of the framework. Section 6.3 defines the holistic framework architecture and in particular it details each of the twenty-two indicators and four parameters created at three different levels i.e. ten key performance indicators to establish the energy performance of the whole system and complete subsystems, twelve performance indicators to evaluate the performance of single units within systems (e.g. a train as part of a fleet) and four parameters capturing data complementing the KPIs and PIs. Section 6.4 discusses how to use this framework providing a comprehensive operationalised description. The chapter conclusions are described in section 6.5.

6.2. Methodological aspects

As indicated in Section 3.4, this Phase 3 of the thesis (Chapters 6 and 7) combines inductive and deductive methodological aspects to develop a holistic and hierarchical framework architecture and its operationalised structure. This involves the definition of the twenty-two indicators and four parameters that form the KEPIs, verified using structured group interviews and stakeholder consultation. This framework is then operationalised by developing a set of instructions, guidelines and schematic representations for framework execution and iteration to aid decision-making processes.

Based on the previous considerations, the research process has taken into account the extensive literature review and assessment undertaken in Chapters 2, 4 and 5. This analysis has led to a preliminary set of indicators subsequently revised and updated through a constructive consultation process including stakeholder representatives from industry, operators and public transport authorities. As a result of this consultation process, a complete set of KEPIs were agreed amongst all stakeholders and validated for illustrative purposes through their use in the assessment of different energy saving measures (Chapter 7). Figure 27 represents this methodological approach.

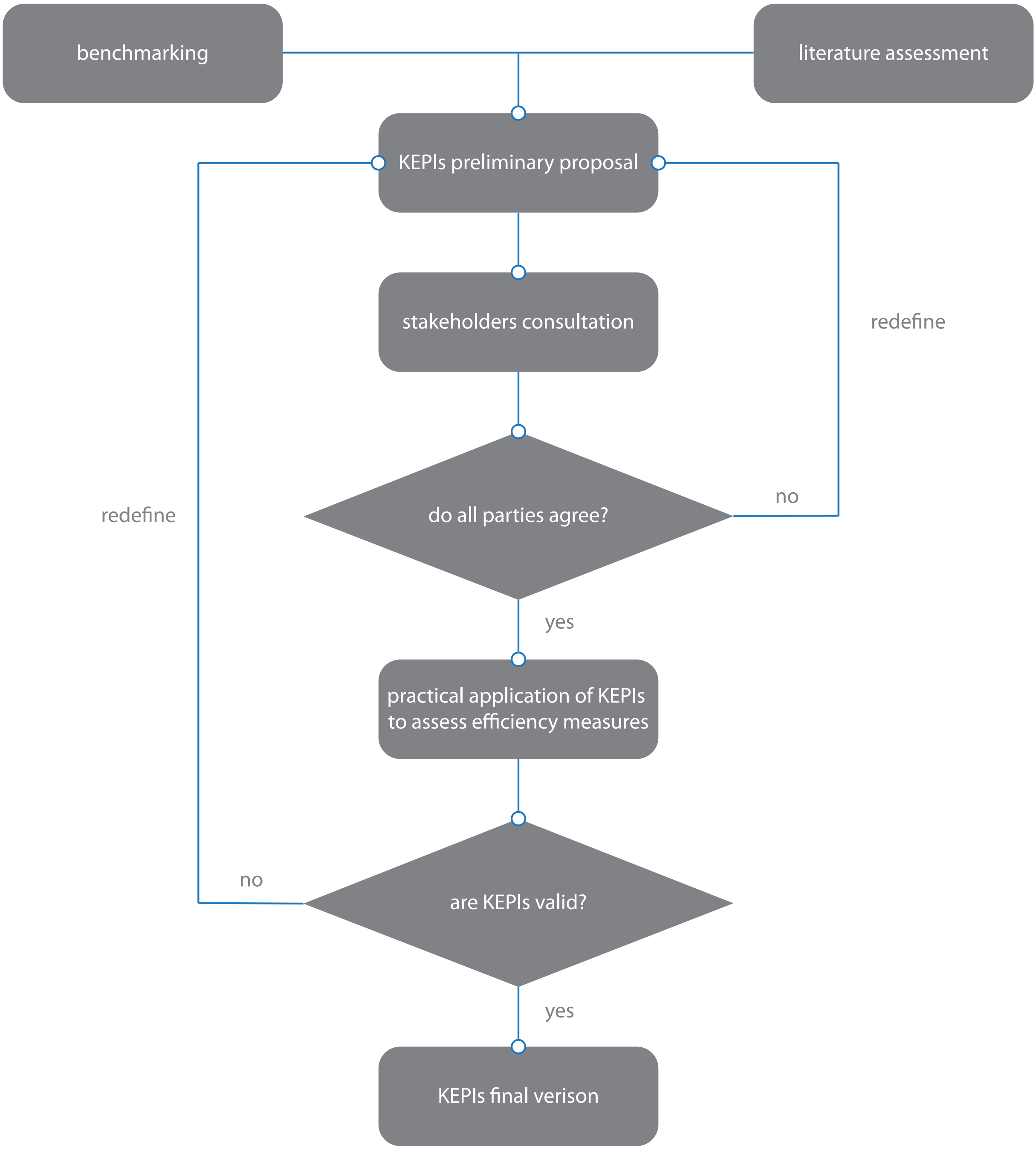

Figure 27. Research methodology for the development of a holistic set of KEPIs

6.2.1.Consultation process

The stakeholder consultation process has been performed using a sequence of techniques underpinned by the theory behind judgemental and conceptual models (Jackson, 2003) as discussed in Chapter 3. These models are used to gather the views of individuals seeking to reinforce the establishment of robust feedback loops as part of methodologies reflecting expert interpretations. Therefore, techniques applied to this Phase 3 of the research include structured and semi-structured interviews which are considered very effective in quantifying judgemental uncertainty (Merkhofer, 1987).

Table 21 below summarises the extent of the consultation implemented based on the previous methodological considerations. In addition to these structured activities, there have been unrecorded internal discussions at each of the stakeholder organisations involved, which are reflected in the outcomes of each of the events, acting as part of the feedback loop between each of these interviews.

Total No. of structured group interviews	Attended structured group interviews	Remote structured group interviews	No. of stakeholder organisations	Total No. of single interviewees*
10	6	4	25	38

*Core interviewees have participated in multiple group interviews

Table 21. Summary of consultation process events undertaken

Twenty-seven interviewees form the core group (identified as Core and Core_support)[14] that include experts from ten stakeholder organisations representing urban public transport authorities and operators from Rome, Milan, Vitoria-Gasteiz, Paris and Istanbul (eleven individuals), equipment and rail systems integrators (fifteen) and academia (one). In addition, as part of the consultation process, a version of the KEPIs was introduced to a wider end-user group (identified as External_user group) formed by public transport authorities and urban rail operators seeking feedback from potential users outside the core consultation group. This group included ten representatives from European urban rail systems operators and city public authorities from Barcelona, Lisbon, Newcastle, Munich, Dusseldorf, Brussels and Oradea (Romania). Table 22 provides an overview of the composition of the consultation group and each of the interviewees involved in the process. The same core group of stakeholders (twenty-seven) has been used as part of the application cases discussed in Chapter 7.

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[14] The sub-group identified as Core included thirteen individuals representing the central collective involved throughout in the consultation process. The Core_support sub-group was formed by a further fourteen stakeholder representatives supporting the process at specific stages.

ID	Role of interviewee	Organisation type	No. of interviews attended	Interview ID
Core	Senior engineer	Expert (Systems integrator)	4	06, 07, 08, 10
Core	Engineering Director	Expert (Systems integrator)	9	01, 03, 04, 05, 06, 07, 08, 09, 10
Core	Senior rail engineer	Equipment manufacturer and systems integrator	2	03, 06
Core	Senior rail engineer	Equipment manufacturer and systems integrator	4	04, 05, 09, 10
Core	Rail energy engineer	Public transport authority and rail systems operator	2	02, 03
Core	Director	Public transport authority and rail systems operator	2	01, 08
Core	Engineering Manager	Public transport authority and rail systems operator	4	01, 02, 03, 08
Core	Senior Energy engineer	Expert (Systems integrator)	6	01, 02, 07, 08, 09, 10
Core	Transport and Energy professor	Expert (academic adviser)	5	02, 04, 05, 06, 08
Core	Eco-design engineer	Expert (Systems integrator)	2	01, 03
Core	Energy Director	Public transport authority and rail systems operator	8	01, 02, 03, 04, 05, 06, 07, 08,
Core	New Line Project Director	Public transport authority and rail systems operator	5	01, 02, 04, 05, 06
Core	Senior Rail Energy Engineer	Expert (Systems integrator)	2	02, 03

Core_support	Rail engineer	Public transport authority and rail systems operator	1	08
Core_support	Senior Director-Board Member	Equipment manufacturer and systems integrator	2	04, 05
Core_support	Director	Public transport authority and rail systems operator	4	01, 02, 03, 08
Core_support	Rail energy senior manager	Equipment manufacturer (vehicles)	3	04, 05, 06
Core_support	Rail Director	Public transport stakeholders association	1	06
Core_support	Rail project manager	Public transport stakeholders association	2	03, 06
Core_support	Rail Energy Engineering manager	Equipment manufacturer and systems integrator	4	02, 04, 05, 09
Core_support	Rail energy engineer	Equipment manufacturer and systems integrator	1	09
Core_support	Rail energy engineering Director	Equipment manufacturer and systems integrator	1	03
Core_support	Energy engineer	Expert (Systems integrator)	1	01
Core_support	Rail energy engineer	Public transport authority and rail systems operator	1	08
Core_support	Rail engineering Director	Equipment manufacturer and systems integrator	5	01, 02, 04, 05, 06
Core_support	Transport Director	Expert (engineering)	2	04, 05
Core_support	Operations adiviser	Public transport authority and rail systems operator	1	09
External_user group	Energy systems engineer	Equipment manufacturer and systems integrator	1	06

External_user group	Sustainability manager	Public transport authority and rail systems operator	1	06
External_user group	Innovation Director	Rail systems operator	1	06
External_user group	Senior manager	Rail systems operator	1	06
External_user group	Senior Rail Energy Engineer	Public transport authority and rail systems operator	1	06
External_user group	Director	Public transport authority and rail systems operator	1	06
External_user group	Director	Public transport authority and rail systems operator	1	06
External_user group	Sustainability and energy manager	Public transport authority and rail systems operator	1	06
External_user group	Senior Rail Engineer	Public transport authority and rail systems operator	1	06
External_user group	Engineering Director	Rail systems operator	1	06
External_user group	Project manager	Rail systems operator	1	06

Table 22. Participants on the consultation process, their background and involvement

Ten group interviews took place over a period of almost two years as part of the consultation process involving thirty-eight different experts from twenty-five organisations representing stakeholders across twelve urban locations. Within this group, there was a main cluster of twenty-seven experts including representatives from five urban rail systems who acted as core to the consultation process. Chapter 7 describes these locations in detail. Table 23 provides a comprehensive overview of this process, summarising the interviews and their key outcomes.

The group interview process followed a structure similar to that of focused interviews and focus groups where the interviewer asks a set of relatively open questions about a specific topic (Bryman, 2015). The ability to provide all participants with the same content allows consistency of stimulus, which in turn facilitates reliability of outcomes that can then be aggregated. The focused aspects together with the group dimension also permit the sustained exchange of views so at the end consensus of outcomes can be reached (Bryman, 2015). This approach has been proven to be very effective for the research carried out in this thesis, establishing a unique feedback process with the stakeholder group. Specifically, for each of the ten group interviews, a document containing a brief explanation and proposed set of systemic indicators within a hierarchical structured framework was circulated together with a list of key topics to discuss. These topics evolved as the consultation process progressed with a chronological alignment between stages in the development of the framework and the interviews e.g. interview No. 01 focused on questions related to the boundaries of the monitoring framework, its core structure and a very preliminary set of indicators while interviews No. 09 and 10 concentrated on the specifics of one particular KPI and other minor details. A mix of six in-person and four remote (via phone) interviews has been used for this process. The feedback provided in between these group interviews was essential in allowing the development of the framework from genesis to the final version described in this Chapter 6 and applied to the illustrative application cases discussed in Chapter 7.

Group interview ID	Date	Type	No. of participants	Participant type	Input and main questions	Main outcome
01	16.02.12	Remote	10	Public transport authority and urban rail systems operator Equipment manufacturer (vehicle) Expert (Systems integrator)	Overview of scope Do you use Energy-related KPIs? Are you aware of existing energy KPIs in urban rail systems? What are they?	Identification of limited number of existing KPIs and need to provide a consistent system-wide approach.
02	29.03.12	In-person	10	Public transport authority and urban rail systems operator Equipment manufacturer (vehicle) Expert (Systems integrator) Expert (academic adviser)	Preliminary hierarchical structure of framework including a selection of KPIs and PIs (v1). Is this proposed structure suitable to comprehensively capture the holistic dimension of energy performance of urban rail systems? If not, what else would be required to achieve this objective? Can these KPIs and PIs be accurately measured at the moment? If not, what would be required to do so? How relevant are variants in operating mode to the overall energy usage in urban rail systems? What aspects of these need to be measured?	Identification and confirmation of the need to have multiple layers on at least two levels of indicators i.e. KPIs and parameters allowing their calculation. Proposed layers include KPIs for whole systems, infrastructure and rolling stock as well as parameter for individual components of those systems/sub-systems. The systemic dimension of the framework is considered essential when coupled with sub-system and component-level indicators. The importance and relevance of different operating modes (e.g. in-service and stabled) influencing energy consumption must be captured by the KPIs. The often overlooked but relevant aspect of thermal energy consumption should also be captured in the KPIs in addition to electrical consumption.

03	02.07.12	Remote	9	Public transport authority and urban rail systems operator Equipment manufacturer (vehicle) Expert (Systems integrator) Expert (academic adviser)	Updated hierarchical structure of framework including a selection of KPIs and PIs (v2). Do the proposed updates to the structure and the preliminary indicators correspond with the necessary measurements to provide a detailed system-wide view of energy performance?	Endorsement of systemic framework architecture and proposed structure ahead of detailed description of agreed areas requiring indicators.
04	12.07.12	In-person	10	Public transport authority and urban rail systems operator Equipment manufacturer (vehicle) Expert (Systems integrator) Expert (academic adviser)	Final update of preliminary framework structure and hierarchical set of KPIs, PIs and parameters (v.3) Can this final framework structure provide a systemic monitoring of energy performance leading to enhanced energy conservation?	Confirmation of suitability of proposed structure for systemic monitoring framework using an approach based on KPIs, PIs and parameters. A KPI related to CO_2 emissions considered appropriate.
05	17.10.12	In-person	10	Public transport authority and urban rail systems operator Equipment manufacturer (vehicle) Expert (Systems integrator) Expert (academic adviser)	Framework structure and indicators overview (v4) First comprehensive draft of hierarchical indicators, their calculation method and potential interdependencies (v5) Do the proposed calculation methods reflect energy flows and consumption in urban rail systems? If not, what is missing? Do proposed interdependencies reflect known behaviour? If not, what is missing?	Proposed calculation for KPI_{02} *specific energy consumption* is considered suitable and realistic. Calculation of total auxiliary consumption and traction usage while possible, it is complex to measure directly and instead could be obtained by extrapolating the values of corresponding PIs i.e. PI_{03} *in-service energy consumption* and PI_{04} *in-service auxiliaries' energy consumption*. The PI related to recovery of braking energy should be defined in a clearer manner. Consensus on the suitability of PI_{03} in reflecting traction drive efficiency, making redundant the need for a specific KPI addressing it.

06	29.11.12	In-person	20	Public transport authority and urban rail systems operator Equipment manufacturer (vehicle) Expert (Systems integrator) Expert (academic adviser) Stakeholder association	Framework structure and indicators overview (v4) Does the proposed hierarchical structure capture the interdependencies and flows that would allow developing a systemic monitoring framework? Do the proposed calculation methods reflect energy flows and consumption in urban rail systems? If not, what is missing?	Consensus regarding suitability of proposed calculation for KPI_{02} *specific energy consumption*. Suitability of KPI_{01} specific CO_{02} emissions clarified and endorsed. Clarifications of scope and calculation method for KPI_{08} and KPI_{09} also endorsed.
07	19.02.13	Remote	4	Public transport authority and urban rail systems operator Expert (Systems integrator)	Updated comprehensive draft of hierarchical indicators, their calculation method and potential interdependencies (v7) Do the updated calculation methods reflect energy flows and consumption in urban rail systems? If not, what is missing? Do the updated proposed interdependencies reflect known behaviour? If not, what is missing?	The proposed calculation of KPI_{05} *traction power supply efficiency* should considered the total net consumption at rolling stock point of coupling. The proposed of KPI_{10} *energy consumption in stations and infrastructure-related equipment* should clarify what energy flows are included. The thermal energy calculation related to waste heat recovery (KPI_{04}) should be clarified. All operators involved in the consultation process should continue revising the proposed updates before the next group interview.
08	21.03.13	In-person	11	Public transport authority and urban rail systems operator Equipment manufacturer (vehicle) Expert (Systems integrator) Expert (academic adviser)	Updated comprehensive draft of hierarchical indicators, their calculation method and potential interdependencies (v8) Do the updated calculation methods reflect energy flows and consumption in urban rail systems? If not, what is missing?	Confirmation of suitability and ability to calculate the whole system energy consumption using the proposed equation for KPI_{02}. Acknowledgement that while waste heat recovery is not considered in all urban rail systems, a KPI related to this would facilitate its appraisal.

09	03.12.13	In-person	6	Public transport authority and urban rail systems operator Equipment manufacturer (vehicle) Expert (Systems integrator) Expert (academic adviser)	Updated comprehensive draft of hierarchical indicators, their calculation method and potential interdependencies (v9) Do the updated calculation methods reflect energy flows and consumption in urban rail systems? If not, what is missing?	Waste heat recovery and thermal energy calculation should reflect the optimisation potential of technologies e.g. free-cooling water pump. The indicators proposed to capture depot consumption and optimisation potential are suitable and fitting within the whole systems approach intended.
10	06.12.13	Remote	4	Equipment manufacturer (vehicle) Expert (Systems integrator)	final comprehensive draft of hierarchical indicators, their calculation method and potential interdependencies (v10) Is this final version of the framework reflecting the aim of systemic monitoring of energy performance leading to energy conservation enhancement? If not, what is missing?	Updated framework structure recognises the effects of sub-systems at system level. Waste heat recovery (KPI_{04}) calculation clarified with respect of thermal energy recuperation. Final update of framework suitability confirmed pending proposed updates on calculation of traction power distribution at system and subsystem level (KPI_{05} and PI_{03}), addition of indicator to better describe depot building consumption (PI_{07}), update on definition of KPI_{02} and KPI_{03} for clearer accountability of both electrical and thermal energy usage (e.g. depots have fuel consumption as well as electrical), addition of parameter (P_{03}) to account for the influence of temperature differential during stabled conditions and graphical version of framework.

Table 23. Summary of outcomes from the structured group interviews as part of the consultation process

6.3. Framework architecture: KEPIs

6.3.1.Requirements

At the core of the systemic monitoring framework for energy conservation is the use of a holistic set of performance indicators. The complexity of urban rail systems may require a large number of indicators covering different aspects of the system energy consumption. 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 situation acting as baseline, which is essential in helping to identify effective energy optimisation and efficiency 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. Table 24 describes the requirements that need to be met.

	Requirement	Description
01	Validity	Valid for all types of urban systems e.g. tramways and metros
02	Inclusive and holistic	KEPIs should provide energy consumption information at different levels e.g. total network, total vehicles, single vehicle auxiliaries. Additionally, they should capture the interdependences between subsystems
03	Wide-ranging	KEPIs should cover a range of specific issues such as energy efficiency, energy recovery, thermal energy management, renewable energy usage and CO_2 emissions
04	Hierarchical	The organization of the different KEPIs should indicate their relative importance in the system performance
05	Soundness	Quantifiable, clearly defined and scientifically valid
06	Descriptive	KEPIs should facilitate evaluation and comparison between different energy efficiency strategies
07	Inspiring	KEPIs do not all have to be measurable within a particular system, but they might stimulate further metering advances in such system
08	Compatible	Suitable for decision-making support in both existing and new systems
09	Representative	KEPIs should provide a basis for comparison between different systems
10	Flexible	KEPIs should be open to further improvement

Table 24. Requirements for the development of a comprehensive set of KEPIs

6.3.2. Development of holistic KEPIs

As described previously, with the aim of providing a holistic and hierarchical assessment of the energy performance of urban rail systems, three different levels of indicators are proposed i.e. key performance indicators, performance indicators and parameters, which together form the energy consumption-related Key Performance Indicators (KEPIs).

Key Performance Indicators (KPIs) are introduced to evaluate the performance of the whole system and complete subsystems e.g. train fleet, complete portfolio of stations. They enable the establishment of fundamental parameters e.g. the system-specific energy usage (and corresponding CO_2 emissions) or the weight in of different subsystems in the global energy consumption. They also reflect how improvements at subsystem level affect the global system performance.

Performance Indicators (PIs) are introduced to analyse the performance of single units within subsystems e.g. a single rail vehicle or station. PIs 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.

Parameters (Ps) are defined to provide completeness of indicators assessment acting as enablers for their calculation as well as an early sign of potential energy conservation needs.

Key Performance Indicators (KPIs)

Ten KPIs have been defined and validated as discussed in section 6.2 as follows:

KPI_{01} Specific CO_2 Emissions

This indicator reflects the yearly amount of CO_2 equivalent (CO_2e) emissions associated with the energy consumption of the whole system per unit of transportation. CO_2e is universally used to describe each of the seven Green House Gases (GHGs) in a common unit (Brander and Davis, 2012). These seven GHGs are: Carbon dioxide (CO2), Methane (CH4), Nitrous oxide (N2O), Hydrofluorocarbons (HFCs), Perfluorocarbons (PFCs) and Sulphur hexafluoride (SF6) (UNFCCC, 2014).

KPI_{01} is measured in kg of CO_2e 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 ($E_{(i)(sys)}$) e.g. electricity, gas, renewable energies and their respective CO_2 conversion factors ($f_{(CO2)(i)}$), which in the case of the UK is provided by Government (Department for Environment food and Rural Affairs, 2014). KPI_{01} is calculated using Equation 1.

$$\mathrm{KPI}_{01} = \frac{\sum_i \mathrm{E}_{(i)(sys)} \cdot \mathrm{f}_{(i)(CO2)}}{\mathrm{N}_{(sys)} \cdot \mathrm{d}_{(sys)}} \qquad (1)$$

Where,

$E_{(i)(sys)}$ is the total yearly energy consumption of the system by energy source (kWh)

$f_{(i)(CO2)}$ is the CO_2 conversion factor for each kind of energy source used in the system (kg CO_{2e}/kWh)

$N_{(sys)}$ is the total number of passengers using the system yearly

$d_{(sys)}$ is the total distance travelled by all trains in the system yearly (km)

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 ($E_{(el)(sys)}$) and thermal energy, ($E_{(th)(sys)}$). This KPI is calculated using equation 2. $E_{(el)(sys)}$ comprises not only the electricity drawn from the public network through the connection point of the rail system with the public power grid (known as point of common coupling), but also all electricity generated within the 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 point of common coupling i.e. the part of the regenerated braking energy that is sent back to the public grid must be accounted as outflow. This KPI can be typically used to establish general performance comparisons between different transport modes. However, its capacity to compare different urban rail systems is limited as each system presents unique characteristics that affect its performance. Furthermore, this is not sufficient 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.

$$\mathrm{KPI}_{02} = \frac{\mathrm{E}_{(el)(sys)} + \mathrm{E}_{(th)(sys)}}{\mathrm{N}_{(sys)} \cdot \mathrm{d}_{(sys)}} \qquad (2)$$

Where:

$E_{(el)(sys)}$ is the yearly net electricity consumption of the system, measured at the common coupling point (kWh)

$E_{(th)(sys)}$ is the total thermal energy consumption of the system yearly (kWh)

$N_{(sys)}$ is the total number of passengers using the system yearly

$d_{(sys)}$ is the total distance travelled by all trains in the system yearly (km)

KPI_{03} *Share of renewable energy*

This indicator refers to the proportion 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. Both electrical and thermal energy coming from renewable sources must be considered as per Equation 3.

$$\mathrm{KPI}_{03} = \frac{\mathrm{E}_{(\mathrm{el})(\mathrm{sys})(\mathrm{ren})} + \mathrm{E}_{(\mathrm{th})(\mathrm{sys})(\mathrm{ren})}}{\mathrm{E}_{(\mathrm{el})(\mathrm{sys})} + \mathrm{E}_{(\mathrm{th})(\mathrm{sys})}} \times 100 \qquad (3)$$

Where:

$E_{(el)(sys)(ren)}$ is the amount of electricity from renewables that is produced and consumed within the system yearly (kWh)

$E_{(th)(sys)(ren)}$ is the amount of thermal energy from renewables that is produced and consumed within the system yearly (kWh)

$E_{(el)(sys)}$ is the yearly net electricity consumption of the system, measured at the common coupling point (kWh)

$E_{(th)(sys)}$ is the total thermal energy consumption of the system yearly (kWh)

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. Waste heat can be typically recovered i) at vehicle level for heating purposes, e.g. from braking resistors or other traction equipment; ii) 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 iii) in depots, e.g. by using cogeneration systems. KPI_{04} aims to quantify the energy savings produced by such measures and is defined as the percentage of the total energy usage that is recovered and reused from waste heat within the system. Equation 4 provides the method to calculate it.

$$\mathrm{KPI}_{04} = \frac{\mathrm{E}_{(\mathrm{th})(\mathrm{sys})(\mathrm{rec})}}{\mathrm{E}_{(\mathrm{el})(\mathrm{sys})} + \mathrm{E}_{(\mathrm{th})(\mathrm{sys})}} \times 100 \qquad (4)$$

Where:

$E_{(th)(sys)(rec)}$ is the amount of energy that is recovered and reused in the form of waste heat within the system yearly (kWh)

$E_{(el)(sys)}$ is the total electricity consumption of the system yearly, measured at the common coupling point as inflow minus outflow (kWh)

$E_{(th)(sys)}$ is the total thermal energy consumption of the system yearly (kWh)

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 point of common coupling and the connection point of the traction power supply grid to the rolling stock i.e. pantograph or collector shoe. It is defined as the yearly net electricity consumption of all trains in the system while they are in service over the total energy consumption for traction purposes measured at substation level, as shown by Equation 5.

$$\mathrm{KPI}_{05} = \frac{\mathrm{E}_{(\mathrm{el})(\mathrm{sys})(\mathrm{veh})(\mathrm{net})}}{\mathrm{E}_{(\mathrm{el})(\mathrm{sys})} - \mathrm{E}_{(\mathrm{el})(\mathrm{sys})(\mathrm{non-trac})}} \times 100 \qquad (5)$$

Where:

$E_{(el)sys)(veh)(net)}$ is the yearly net electricity consumption of all trains in the system while they are in service (kWh)

$E_{(el)(sys)}$ is the total electricity consumption of the system yearly, measured at the common coupling point as inflow minus outflow (kWh)

$E_{(el)(sys)(non\text{-}trac)}$ is the yearly non-traction electricity consumption of the system (kWh)

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. 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. This indicator is calculated using equation 6.

$$\mathrm{KPI}_{06} = \frac{\mathrm{E}_{(\mathrm{el})(\mathrm{sys})(\mathrm{veh})(\mathrm{net})} - \mathrm{E}_{(\mathrm{el})(\mathrm{sys})(\mathrm{veh})(\mathrm{aux})}}{\mathrm{N}_{(\mathrm{sys})} \cdot \mathrm{d}_{(\mathrm{sys})}} \qquad (6)$$

Where:

$E_{(el)(sys)(veh)(net)}$ is the yearly net electricity consumption of all trains in the system while they are in service (kWh)

$E_{(el)(sys)(veh)(aux)}$ is the electricity consumed by the auxiliary systems of all trains in the system while they are in service (kWh)

$N_{(sys)}$ is the total number of passengers using the system yearly

$d_{(sys)}$ is the total distance travelled by all trains in the system yearly (km)

KPI_{07} In-service auxiliaries’ energy consumption

This KPI expresses the annual energy consumption of all vehicles’ auxiliaries in the system per passenger-km. this indicator can be applied to evaluate different energy efficiency measures focused on, for instance, 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 ability of this indicator to compare different rail systems is limited. KPI_{07} is calculated using Equation 7 as follows:

$$\mathrm{KPI}_{07} = \frac{\mathrm{E}_{(\mathrm{el})(\mathrm{sys})(\mathrm{veh})(\mathrm{aux})}}{\mathrm{N}_{(\mathrm{sys})} \cdot \mathrm{d}_{(\mathrm{sys})}} \tag{7}$$

Where:

$E_{(el)sys)(veh)(aux)}$ is the electricity consumed by the auxiliary systems of all trains in the system while they are in service (kWh)

$N_{(sys)}$ is the total number of passengers using the system yearly

$d_{(sys)}$ is the total distance travelled by all trains in the system yearly (km)

KPI_{08} Braking energy recovery

This indicator is intended to quantify the energy savings achieved in the whole system through the use of regenerative braking technologies. It is defined as the percentage of the yearly gross traction energy consumption that is recovered during braking of all trains in the system. This includes both the electricity sent back to the traction power supply grid and the energy reused and stored within the vehicles themselves. Gross traction energy consumption is understood as 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.

KPI_{08} 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. Therefore, this indicator is designed for comparisons within a given system rather than between systems. Equation 8 shows how to calculate it.

$$\mathrm{KPI}_{08} = \frac{\mathrm{E}_{(\mathrm{el})(\mathrm{sys})(\mathrm{veh})(\mathrm{reg})}}{\mathrm{E}_{(\mathrm{el})(\mathrm{sys})(\mathrm{veh})(\mathrm{gross})}} \mathrm{x}100 \qquad (8)$$

Where:

$E_{(el)(sys)(veh)(reg)}$ is the electricity recovered through the use of regenerative braking technologies within the whole system yearly (kWh)

$E_{(el)(sys)(veh)(gross)}$ is the yearly gross electricity consumption of all trains in the system while they are in service (kWh)

KPI₀₉ Energy consumption in depots

This indicator computes the total energy consumption in depots, comprising the energy used by stabled trains and the thermal and electrical energy consumption of depot buildings, as expressed by Equation 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, as this is considered a readily available parameter that is directly related to the energy consumption in depots. If used to compare depots' performance between different systems, climatic conditions in the city/region should be taken into account as they may affect the consumption of both vehicles and buildings.

$$\mathrm{KPI}_{09} = \frac{\mathrm{E}_{(\mathrm{el})(\mathrm{sys})(\mathrm{park})} + \mathrm{E}_{(\mathrm{el})(\mathrm{sys})(\mathrm{dep})} + \mathrm{E}_{(\mathrm{th})(\mathrm{sys})(\mathrm{dep})}}{\mathrm{C}_{(\mathrm{sys})}} \qquad (9)$$

Where:

$E_{(el)(sys)(park)}$ is the yearly electricity consumption of all trains in the system while parked at depots (kWh)

$E_{(el)(sys)(dep)}$ is the yearly electricity consumption of all depot buildings in the system (kWh)

$E_{(th)(sys)(dep)}$ is the yearly thermal energy consumption of all depot buildings in the system (kWh)

$C_{(sys)}$ is the total passenger capacity of all trains in the system

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 network. The infrastructure-related equipment typically comprises tunnel ventilation systems as a major energy consumer. However, other equipment could be included in this KPI depending on the particular case of the given system. Energy use in stations comprises both thermal and electrical energy consumptions. 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. Equation 10 provides the method to calculate its value.

$$\mathrm{KPI}_{10} = \frac{\mathrm{E}_{(\mathrm{el})(\mathrm{sys})(\mathrm{st})} + \mathrm{E}_{(\mathrm{th})(\mathrm{sys})(\mathrm{st})} + \mathrm{E}_{(\mathrm{el})(\mathrm{sys})(\mathrm{tun})}}{\mathrm{L}_{(\mathrm{sys})}} \qquad (10)$$

Where:

$E_{(el)(sys)(st)}$ is the yearly electricity consumption of all stations in the system (kWh)

$E_{(th)(sys)(st)}$ is the yearly thermal energy consumption of all depot buildings in the system (kWh)

$E_{(el)(sys)(tun)}$ is the yearly electricity consumption of all tunnel ventilation equipment in the system (kWh)

$L_{(sys)}$ total network length (km)

Performance Indicators (PIs)

PIs are intended to establish the effect of multiple energy saving measures on specific parts of the system, which can be done either by testing the actual technology/strategy on site or via simulations. Thus, they provide fundamental information to support decision-making on the suitability of a given intervention to be implemented throughout the entire system. Knowledge of detailed duty cycles and operational regimes is indispensable for these PIs to provide valid contrasting information. Twelve PIs have been defined and validated as discussed in section 6.2 as follows:

PI_{01} *Electric substation efficiency*

This indicator is intended to assess the effectiveness of different energy efficiency interventions to reduce losses in substations, particularly in their main components i.e. transformers and rectifiers. It is defined as the average power transformation efficiency in a single substation for a given load cycle and over a given period of time. It may be obtained as the total energy flow at the entrance of the substation (connection point between the transformer and the main distribution grid) over the total energy flow at its exit over the reference time period. If calculated for all the substations in the system, it enables the efficiency of the traction power distribution network from KPI_{05} to be obtained. Equation 11 shows how to calculate it.

$$\mathrm{PI}_{01} = \frac{\mathrm{E}_{(\mathrm{el})(\mathrm{sub})(\mathrm{out})}}{\mathrm{E}_{(\mathrm{el})(\mathrm{sub})(\mathrm{in})}} \mathrm{x}100 \tag{11}$$

Where:

$E_{(el)(sub)(out)}$ is the electricity flow measured at the exit of a single substation for a given period of time (kWh)

$E_{(el)(sub)(in)}$ is the electricity flow measured at the entrance of a single substation for a given period of time (kWh)

PI_{02} Power distribution line efficiency

This PI aims at capturing the efficiency of interventions intended to reduce losses on the power distribution line e.g. catenary or third rail. It considers the total energy flow entering the rolling stock against the power measured exiting the substations in a given line section and under a predefined load cycle, as shown in equation 12.

$$\mathrm{PI}_{02} = \frac{\mathrm{E}_{(\mathrm{el})(\mathrm{veh})(\mathrm{net})}}{\mathrm{E}_{(\mathrm{el})(\mathrm{sub})(\mathrm{out})}} \mathrm{x}\,100 \tag{12}$$

Where:

$E_{(el)(veh)(net)}$ is the net electricity consumed by a single rail vehicle during a predefined duty cycle (kWh)

$E_{(el)(sub)(out)}$ is the electricity flow measured at the exit of a single substation for a given period of time (kWh)

PI_{03} In-service traction energy consumption

This indicator has been defined to assess the energy performance of individual vehicles as well as the effect of different interventions in improving their traction system efficiency. It is expressed as the average traction energy used by one train during a given duty cycle which must be determined by predefined parameters e.g. passenger load, route, driving style. Equation 13 indicates the calculation method.

$$\mathrm{PI}_{03} = \frac{\mathrm{E}_{(\mathrm{el})(\mathrm{veh})(\mathrm{net})} - \mathrm{E}_{(\mathrm{el})(\mathrm{veh})(\mathrm{aux})}}{\mathrm{N}_{(\mathrm{veh})} \cdot \mathrm{d}_{(\mathrm{veh})}} \tag{13}$$

Where:

$E_{(el)(veh)(net)}$ is the net electricity consumed by a single rail vehicle during a predefined duty cycle (kWh)

$E_{(el)(veh)(aux)}$ is the electricity consumed by the auxiliary systems of a single rail vehicle during a predefined duty cycle (kWh)

$N_{(veh)}$ is the total number of passengers predefined in the given duty cycle

$d_{(veh)}$ is the total distance travelled by the vehicle in the given duty cycle (km)

PI_{04} In-service auxiliaries' energy consumption

PI_{04} accounts for the auxiliaries' energy consumption of a single vehicle during a predefined duty cycle, as shown in equation 14. Given the significant contribution of HVAC equipment to this consumption, target comfort parameters and climate conditions must be specified for such a duty cycle. This PI permits the evaluation of different measures to reduce the energy consumption of vehicle systems such as lighting, heating or air conditioning.

$$\mathrm{PI}_{04} = \frac{\mathrm{E}_{(\mathrm{el})(\mathrm{veh})(\mathrm{aux})}}{\mathrm{N}_{(\mathrm{veh})} \cdot \mathrm{d}_{(\mathrm{veh})}} \tag{14}$$

Where:

$E_{(el)(veh)(aux)}$ is the electricity consumed by the auxiliary systems of a single rail vehicle during a predefined duty cycle (kWh)

$N_{(veh)}$ is the total number of passengers predefined in the given duty cycle

$d_{(veh)}$ is the total distance travelled by the vehicle in the given duty cycle (km)

PI_{05} Braking energy recovery

This indicator enables the energy savings achieved at vehicle level by using different regenerative braking technologies to be assessed. It is defined as the percentage of the gross traction power consumption measured at pantograph level i.e. regenerated during the successive braking processes of a single vehicle during a given duty cycle, as shown in equation 15 below.

$$\mathrm{PI}_{05} = \frac{\mathrm{E}_{(\mathrm{el})(\mathrm{veh})(\mathrm{reg})}}{\mathrm{E}_{(\mathrm{el})(\mathrm{veh})(\mathrm{gross})}} \mathrm{x}100 \tag{15}$$

Where*:*

$E_{(el)(veh)(reg)}$ is the electricity recovered through the use of regenerative braking technologies for a single train over a predefined duty cycle (kWh)

$E_{(el)(sys)(veh)(gross)}$ is the gross electricity consumption of a single train over a predefined duty cycle (kWh)

PI_{06} *Braking energy recovery efficiency*

This PI is intended to complement PI_{05} in the evaluation of strategies and technologies to increase the use of regenerative braking energy in urban rail systems. It is defined as the percentage of the maximum recovery potential that is actually achieved by a single vehicle during a particular duty cycle (see equation 16), giving an indication of how efficient the braking energy recovery is.

$$\mathrm{PI}_{06} = \frac{\mathrm{E}_{(\mathrm{el})(\mathrm{veh})(\mathrm{reg})}}{\mathrm{E}_{(\mathrm{el})(\mathrm{veh})(\mathrm{reg})(\mathrm{max})}} \mathrm{x}100 \tag{16}$$

Where:

$E_{(el)(veh)(reg)}$ is the electricity recovered through the use of regenerative braking technologies for a single train over a predefined duty cycle (kWh)

$E_{(el)(veh)(reg)(max)}$ is the maximum potential for regenerative braking energy recovery in a predefined duty cycle (kWh)

PI_{07} *Depot building's energy consumption*

This PI computes the total energy use in a single depot building per unit of area, as defined by equation 17. It therefore allows the specific energy savings generated by interventions aiming to minimise the energy consumption in these buildings to be assessed.

$$\mathrm{PI}_{07} = \frac{\mathrm{E}_{(\mathrm{el})(\mathrm{dep})} + \mathrm{E}_{(\mathrm{th})(\mathrm{dep})}}{\mathrm{A}_{(\mathrm{dep})}} \tag{17}$$

Where:

$E_{(el)(dep)}$ is the thermal energy consumption of a particular depot building under a predefined duty cycle (kWh)

$E_{(th)(dep)}$ is the thermal energy consumption of a particular depot building under a predefined duty cycle (kWh)

$A_{(dep)}$ is the net floor area of the given depot building (m^2)

PI_{08} *Parked mode vehicle's energy consumption*

The aim of this PI is to evaluate energy efficiency measures seeking to reduce consumption of trains in parked mode. It is calculated (see equation 18) as the total energy used by a single train in parked mode over a given duty cycle, which should define preconditioning, cleaning and hibernating functions.

$$\mathrm{PI}_{08} = \frac{\mathrm{E}_{(\mathrm{el})(\mathrm{veh})(\mathrm{park})}}{\mathrm{C}_{(\mathrm{veh})}} \tag{18}$$

Where:

$E_{(el)(veh)(park)}$ is the electricity consumption of a single train while parked at the depot over a predefined duty cycle (kWh)

$C_{(veh)}$ is the total passenger capacity of the given train

PI_{09} Station HVAC energy consumption

This PI captures the energy used for Heating, Ventilation and Air Conditioning (HVAC) in a given single station as a function of its surface area and is calculated using equation 19. It requires predefining comfort parameters such as temperature or air quality levels in order to assess the potential energy savings achieved through different energy efficiency measures.

$$\mathrm{PI}_{09} = \frac{\mathrm{E}_{(\mathrm{el})(\mathrm{st})(\mathrm{HVAC})} + \mathrm{E}_{(\mathrm{th})(\mathrm{st})(\mathrm{HVAC})}}{\mathrm{A}_{(\mathrm{st})}} \tag{19}$$

Where:

$E_{(el)(st)(HVAC)}$ is the electricity consumption of HVAC systems in a particular station under predefined working conditions (kWh)

$E_{(th)(st)(HVAC)}$ is the thermal energy consumption of HVAC systems in a particular station under predefined working conditions (kWh)

$A_{(st)}$ is the net floor area of the given station (m^2)

PI_{10} Station lighting and information systems energy usage

This PI quantifies the energy used for lighting and information purposes within a single station in relation to its surface area (see equation 20). This indicator can be useful in assessing the effectiveness of different energy saving measures affecting these systems, provided the standards of service are previously defined.

$$\mathrm{PI}_{10} = \frac{\mathrm{E}_{(\mathrm{el})(\mathrm{st})(\mathrm{light})}}{\mathrm{A}_{(\mathrm{st})}} \tag{20}$$

Where:

$E_{(el)(st)(light)}$ is the electricity consumption of lighting and information systems in a particular station under predefined working conditions (kWh)

$A_{(st)}$ is the net floor area of the given station (m^2)

PI_{11} Station passenger flow-related energy usage

This indicator accounts for the energy consumption of escalators, lifts and other passenger conveyor systems in stations. Given a predefined pattern of passengers flow, it allows establishing the energy savings achieved through different interventions at station level. PI_{11} is obtained using equation 21 below.

$$\mathrm{PI}_{11} = \frac{\mathrm{E}_{(\mathrm{el})(\mathrm{st})(\mathrm{PF})}}{\mathrm{N}_{(\mathrm{st})(\mathrm{PF})}} \qquad (21)$$

Where:

$E_{(el)(st)(PF)}$ is the electricity consumption of a particular passenger flow over a predefined time and usage pattern (kWh)

$N_{(st)(PF)}$ is the number of passengers using an specific conveyor facility e.g. escalators

PI_{12} Tunnel ventilation energy consumption

This indicator refers to the energy consumed by the mechanical ventilation systems installed in underground networks to reduce their tunnel temperature. Equation 22 indicates how to obtain this value. It is necessary to have a definition of a standard tunnel section along with its traffic load conditions and air quality requirements in order to use this PI in the evaluation of potential energy efficiency measures.

$$\mathrm{PI}_{12} = \frac{\mathrm{E}_{(\mathrm{el})(\mathrm{tun})}}{\mathrm{V}_{(\mathrm{tun})}} \qquad (22)$$

Where:

$E_{(el)(tun)}$ is the electricity consumption of tunnel ventilation systems for a specific tunnel section under predefined working conditions (kWh)

$V_{(tun)}$ is the air volume within a specific tunnel section (m^3)

<u>Parameters (Ps)</u>

Four parameters complementing the twenty-two indicators have been defined and validated as discussed in section 6.2 as follows:

P_{01} Mean supply voltage ($U_{(mean)}$)

This parameter consists of the mean useful voltage at the point of coupling between the power supply network and the vehicle according to the European Standard EN-50388 which deals with the definition and quality requirements of the power supply at the interface between traction units and fixed installations (CENELEC, 2012). P_{01}

is a key symptom of the quality of the power supply as well as an indirect measure of energy losses in the supply system.

P_{02} Mean in-vehicle temperature differential during service ($\mathbf{\Delta\overline{T}_{(veh)(out)}}$)

Intended to serve as a measure of passenger comfort quality, this parameter monitors the mean difference between the interior temperature of in-service vehicles ($T_{(veh)}$) and the outdoor temperature ($T_{(out)}$). This measure could be evaluated daily, monthly or seasonally, depending on the degree of detail required for the assessment. Furthermore, P_{02} could facilitate the development and validation of energy efficiency measures based on modifying the target comfort temperature i.e. the parameter could reveal that the actual target temperature is disproportionate in relation to the outdoor temperature, which can create passenger discomfort and lead to suboptimum energy usage.

P_{03} Mean temperature in parked mode ($\mathbf{\overline{T}_{(veh)(park)}}$)

This parameter reflects the mean temperature inside vehicles while in parked mode. The measurement can contribute to the development and evaluation of energy saving strategies aimed to reduce the HVAC consumption during stabling hours. Unlike P_{02}, this parameter should be evaluated on an hourly basis as low temperature peaks may cause damage to different electronic components in the vehicle.

P_{04} Mean tunnel temperature differential ($\mathbf{\Delta\overline{T}_{(tun)(out)}}$)

The difference of temperatures between the air in tunnels ($T_{(tun)}$) and the surface ($T_{(out)}$) can be used as a sign of the effectiveness of tunnel ventilation systems and therefore help to define and evaluate interventions aimed at reducing such systems energy consumption.

6.3.3. Integration and framework architecture

The previous section has described in detail each of the indicators and parameters comprising the KEPIs and acting as a core of the monitoring framework proposed. Table 25 provides an overview of this complete set.

	KEPIs component	Definition	Calculation	Units
KPI_{01}	Specific CO_2 emissions	Yearly amount of CO_2e emissions associated with the whole system energy consumption per unit of transportation	$\mathrm{KPI_{01}} = \frac{\sum_{\mathrm{i}} \mathrm{E_{(i)(sys)}} \cdot \mathrm{f_{(i)(CO2)}}}{\mathrm{N_{(sys)}} \cdot \mathrm{d_{(sys)}}}$	Kg (CO_2e)/pax-km
KPI_{02}	Specific energy consumption	Global efficiency of the system measured by total yearly energy consumption per passenger-km	$\mathrm{KPI_{02}} = \frac{\mathrm{E_{(el)(sys)}} + \mathrm{E_{(th)(sys)}}}{\mathrm{N_{(sys)}} \cdot \mathrm{d_{(sys)}}}$	kWh/pax-km
KPI_{03}	Share of renewable energy	Proportion of yearly total energy consumption at system level supplied by renewable sources within the system	$\mathrm{KPI_{03}} = \frac{\mathrm{E_{(el)(sys)(ren)}} + \mathrm{E_{(th)(sys)(ren)}}}{\mathrm{E_{(el)(sys)}} + \mathrm{E_{(th)(sys)}}} \times 100$	%
KPI_{04}	Waste heat recovery	Proportion of total energy consumption that is recovered and reused from waste heat	$\mathrm{KPI_{04}} = \frac{\mathrm{E_{(th)(sys)(rec)}}}{\mathrm{E_{(el)(sys)}} + \mathrm{E_{(th)(sys)}}} \times 100$	%
KPI_{05}	Traction power supply efficiency	Yearly net energy consumption of all in-service trains in relation to the total traction consumption measured at substation level	$\mathrm{KPI_{05}} = \frac{\mathrm{E_{(el)(sys)(veh)(net)}}}{\mathrm{E_{(el)(sys)}} - \mathrm{E_{(el)(sys)(non-trac)}}} \times 100$	%
KPI_{06}	In-service traction energy consumption	Yearly consumption for traction purposes (i.e. excluding auxiliaries) in the system per unit of transportation	$\mathrm{KPI_{06}} = \frac{\mathrm{E_{(el)(sys)(veh)(net)}} - \mathrm{E_{(el)(sys)(veh)(aux)}}}{\mathrm{N_{(sys)}} \cdot \mathrm{d_{(sys)}}}$	kWh/pax-km
KPI_{07}	In-service auxiliaries' energy consumption	Yearly consumption of all vehicles' auxiliaries per unit of transportation	$\mathrm{KPI_{07}} = \frac{\mathrm{E_{(el)(sys)(veh)(aux)}}}{\mathrm{N_{(sys)}} \cdot \mathrm{d_{(sys)}}}$	kWh/pax-km
KPI_{08}	Braking energy recovery	Proportion of total yearly gross consumption for traction purposes that is recovered during braking (all trains)	$\mathrm{KPI_{08}} = \frac{\mathrm{E_{(el)(sys)(veh)(reg)}}}{\mathrm{E_{(el)(sys)(veh)(gross)}}} \mathrm{x}100$	%
KPI_{09}	Energy consumption in depots	Total yearly consumption in depots in relation to the passenger capacity of the given system	$\mathrm{KPI_{09}} = \frac{\mathrm{E_{(el)(sys)(park)}} + \mathrm{E_{(el)(sys)(dep)}} + \mathrm{E_{(th)(sys)(dep)}}}{\mathrm{C_{(sys)}}}$	kWh/pax

KPI$_{10}$	Energy consumption in stations and infrastructure-related equipment	Total energy consumption of all stations and infrastructure-related equipment per km of network	$\mathrm{KPI_{10}} = \frac{\mathrm{E_{(el)(sys)(st)}} + \mathrm{E_{(th)(sys)(st)}} + \mathrm{E_{(el)(sys)(tun)}}}{\mathrm{L_{(sys)}}}$	kWh/km
PI$_{01}$	Electric substation efficiency	Proportion of total energy flow at the exit of a particular substation related to the total energy flow at its entrance for a given load cycle	$\mathrm{PI_{01}} = \frac{\mathrm{E_{(el)(sub)(out)}}}{\mathrm{E_{(el)(sub)(in)}}} \mathrm{x100}$	%
PI$_{02}$	Power distribution line efficiency	Proportion of total energy flow entering rolling stock related to the total energy flow exiting the substation for a given section of line under a predefined load cycle	$\mathrm{PI_{02}} = \frac{\mathrm{E_{(el)(veh)(net)}}}{\mathrm{E_{(el)(sub)(out)}}} \mathrm{x\ 100}$	%
PI$_{03}$	In-service traction energy consumption	Traction energy consumption of a single vehicle per unit of transportation for a given duty cycle	$\mathrm{PI_{03}} = \frac{\mathrm{E_{(el)(veh)(net)}} - \mathrm{E_{(el)(veh)(aux)}}}{\mathrm{N_{(veh)}} \cdot \mathrm{d_{(veh)}}}$	kWh/pax-km
PI$_{04}$	In-service auxiliaries' energy consumption	Auxiliaries' energy consumption of a single vehicle per unit of transportation for a predefined duty cycle	$\mathrm{PI_{04}} = \frac{\mathrm{E_{(el)(veh)(aux)}}}{\mathrm{N_{(veh)}} \cdot \mathrm{d_{(veh)}}}$	kWh/pax-km
PI$_{05}$	Braking energy recovery	Proportion of a single vehicle's gross traction power consumption measured at pantograph level that is regenerated during braking for a given duty cycle	$\mathrm{PI_{05}} = \frac{\mathrm{E_{(el)(veh)(reg)}}}{\mathrm{E_{(el)(veh)(gross)}}} \mathrm{x100}$	%
PI$_{06}$	Braking energy recovery efficiency	Proportion of the maximum potential for regenerative braking energy recovery that is actually achieved by a single vehicle during a given duty cycle	$\mathrm{PI_{06}} = \frac{\mathrm{E_{(el)(veh)(reg)}}}{\mathrm{E_{(el)(veh)(reg)(max)}}} \mathrm{x100}$	%
PI$_{07}$	Depot building energy consumption	Energy use in a single depot building per unit of net floor area for a predefined operational cycle	$\mathrm{PI_{07}} = \frac{\mathrm{E_{(el)(dep)}} + \mathrm{E_{(th)(dep)}}}{\mathrm{A_{(dep)}}}$	kWh/m^2
PI$_{08}$	Parked-mode vehicle energy consumption	Energy consumption of a single vehicle in parked-mode per passenger capacity unit for a given duty cycle	$\mathrm{PI_{08}} = \frac{\mathrm{E_{(el)(veh)(park)}}}{\mathrm{C_{(veh)}}}$	kWh/pax

PI_{09}	Station HVAC energy consumption	Energy consumed by HVAC systems in a single station per surface area, given a predefined operational cycle	$PI_{09} = \frac{E_{(el)(st)(HVAC)} + E_{(th)(st)(HVAC)}}{A_{(st)}}$	kWh/m^2
PI_{10}	Station lighting and information systems energy usage	Energy used for lighting and information purposes within an individual station in relation to its surface area under a predefined operational cycle	$PI_{10} = \frac{E_{(el)(st)(light)}}{A_{(st)}}$	kWh/m^2
PI_{11}	Station passenger flow-related energy usage	Specific energy consumption of a single passenger flow-related system (e.g. lifts, escalators and other conveyor systems) for a given operational regime	$PI_{11} = \frac{E_{(el)(st)(PF)}}{N_{(st)(PF)}}$	kWh/m^2
PI_{12}	Tunnel ventilation energy consumption	Energy used by ventilation systems in a specific underground section related to tunnel volume under predefined operational conditions	$PI_{12} = \frac{E_{(el)(tun)}}{V_{(tun)}}$	kWh/m^3
P_{01}	Mean supply voltage	Mean useful voltage at the point of coupling between the power supply network and the vehicle	-	V
P_{02}	Mean in-vehicle temperature differential during service	Mean difference between the interior temperature of in-service vehicles and the exterior temperature.	$P_{02} = \Delta\overline{T}_{(veh)(out)} = \overline{T}_{veh} - \overline{T}_{out}$	^{O}C
P_{03}	Mean temperature in parked mode	Mean temperature inside vehicles while on parked mode	$P_{03} = \bar{T}_{veh}$	^{O}C
P_{04}	Mean tunnel temperature differential	Mean difference of the air temperature in tunnels and on the surface	$P_{04} = \Delta\overline{T}_{(tun)(out)} = \overline{T}_{tun} - \overline{T}_{out}$	^{O}C

Table 25. Detailed overview of the complete set of KPIs, PIs and Parameters forming the systemic KEPIs structrure

The integration of these KEPIs into a meaningful systemic framework for monitoring energy performance and conservation in urban rail systems results in the proposed framework architecture described in Figure 28. It covers the energy performance of the whole system and its main subsystems i.e. the power supply network, rolling stock, depots and infrastructure, as illustrated in this diagram.

The framework has been designed for system-wide coverage, which by the very nature of urban rail systems requires adaptability and flexibility as key characteristics. Therefore, while the holistic set described in this thesis is fully inclusive and is intended to cover all relevant levels of energy usage, it is not exclusive. The comprehensive set of KEPIs does not constitute a fixed list, but one that refers to most relevant consumptions at system, subsystem and component levels in typical urban rail systems as identified in Chapter 2. Depending on the particular characteristics of each system, additional indicators and parameters could be added to assess the energy performance of facilities that contribute significantly to the energy breakdown of that particular system; e.g. cooling equipment of railway technical rooms in hot climate conditions, the signalling systems, underground water pumps. It is also relevant to note that the PIs and parameters included in this set of KEPIs may be used in the calculation of the defined KPIs. For instance, it would be possible to establish KPI_{09} by knowing PI_{07} and PI_{08} for all depot buildings and parked vehicles in the system, respectively. More relationships between different PIs and KPIs can be extracted from Figure 28.

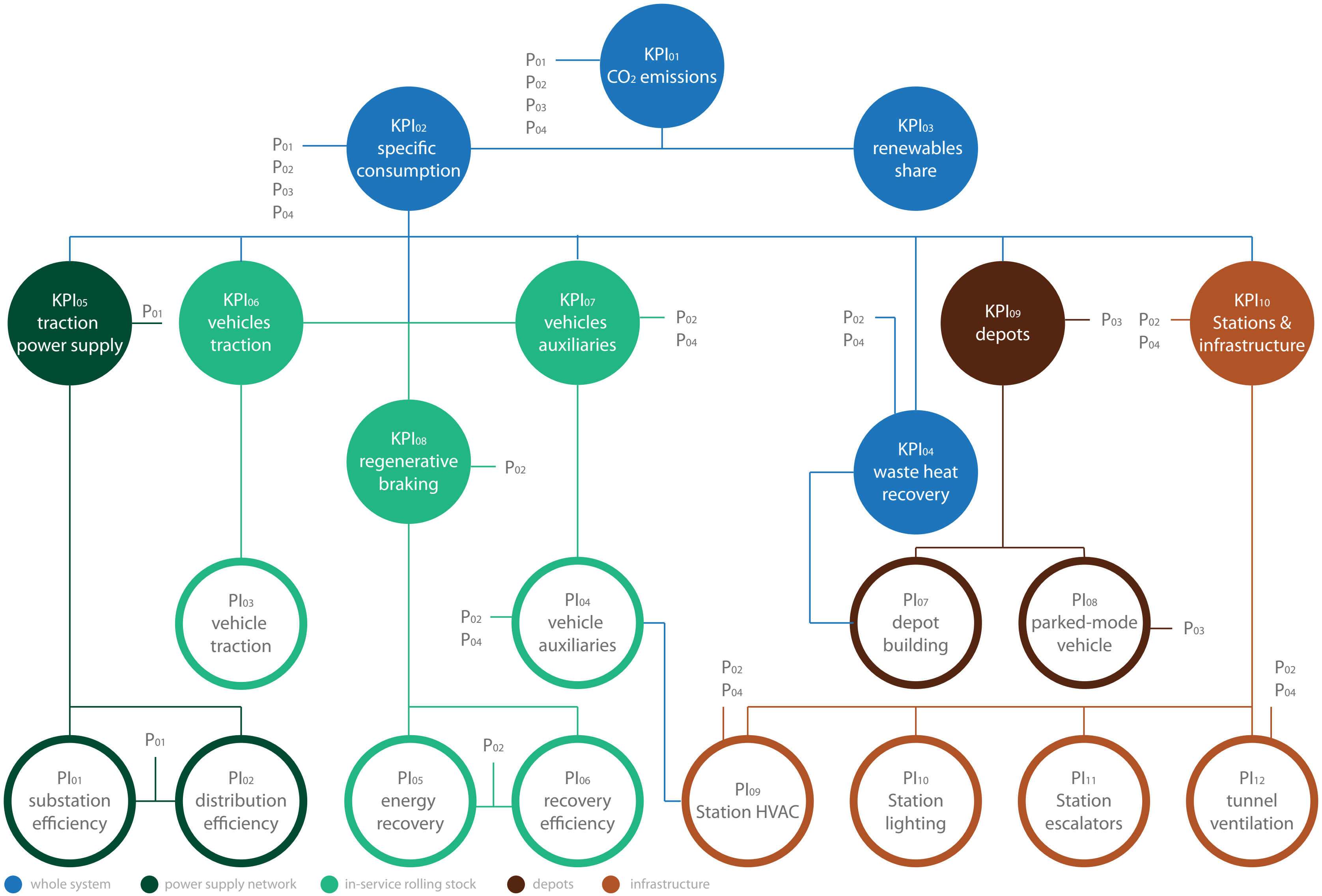

Figure 28. Framework architecture for systemic monitoring of energy performance in urban rail systems.

6.4. Framework architecture: Implementation aspects

6.4.1.Procedure to apply the framework

To implement or operationalise the framework proposed using the KEPIs set defined in the previous section, a number of aspects need to be considered.

Firstly, KPIs are useful to provide a complete description of the actual energy usage in the system from a baseline of on-site measurements. This information subsequently facilitates identification of key areas for improvement, establishing target energy savings and preselecting groups of actions to achieve them. Such measures require evaluation at unit level (e.g. single train) before their implementation at system level (e.g. fleet). That is, it is necessary to assess, either experimentally or by simulations, their influence in improving the energy efficiency or optimising the consumption in a particular unit, under predefined conditions. The defined PIs are specifically developed for this purpose.

The quantification of the effects of interventions at unit level can then be estimated at system level. Given the difficulty and costs involved in testing measures at large scale, this process normally requires the use of computer simulations. In certain cases e.g. lighting replacement in stations, the energy savings extrapolation from a single unit to the whole system is reasonably straightforward and does not require complex simulations. However, other interventions such as introducing on-board regenerative braking technologies or applying eco-driving strategies do 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, or reduction in available braking energy due to energy efficient driving.

Once a new energy consumption scenario is defined by recalculating the relevant KPIs, a comparison against the current situation (baseline) is performed to determine whether the energy savings at system level are still significant. Due to the aforementioned subsystem’s interactions and interdependencies the energy optimisation effect of some measures could become negligible at system level. If so, a cost-benefit assessment of the specific measure would be required to decide on its ultimate implementation. Lastly, the proposed KPIs can be used to monitor the real performance of interventions once they have been deployed, providing valuable information leading to possible readjustments to maximise optimisation potential, raising energy conservation levels.

Additional KPIs, PIs or parameters can be removed or added depending on the characteristics of a given system. Nevertheless, the methodology and framework described herein is universal and valid to be applied by any urban rail system to successfully monitor, assess and benchmark their energy consumption performance and conservation prospects. Figure 29 provides guidance in implementing the framework, illustrating the role of the proposed set of KEPIs in assessing and optimising the energy consumption of urban rail systems.

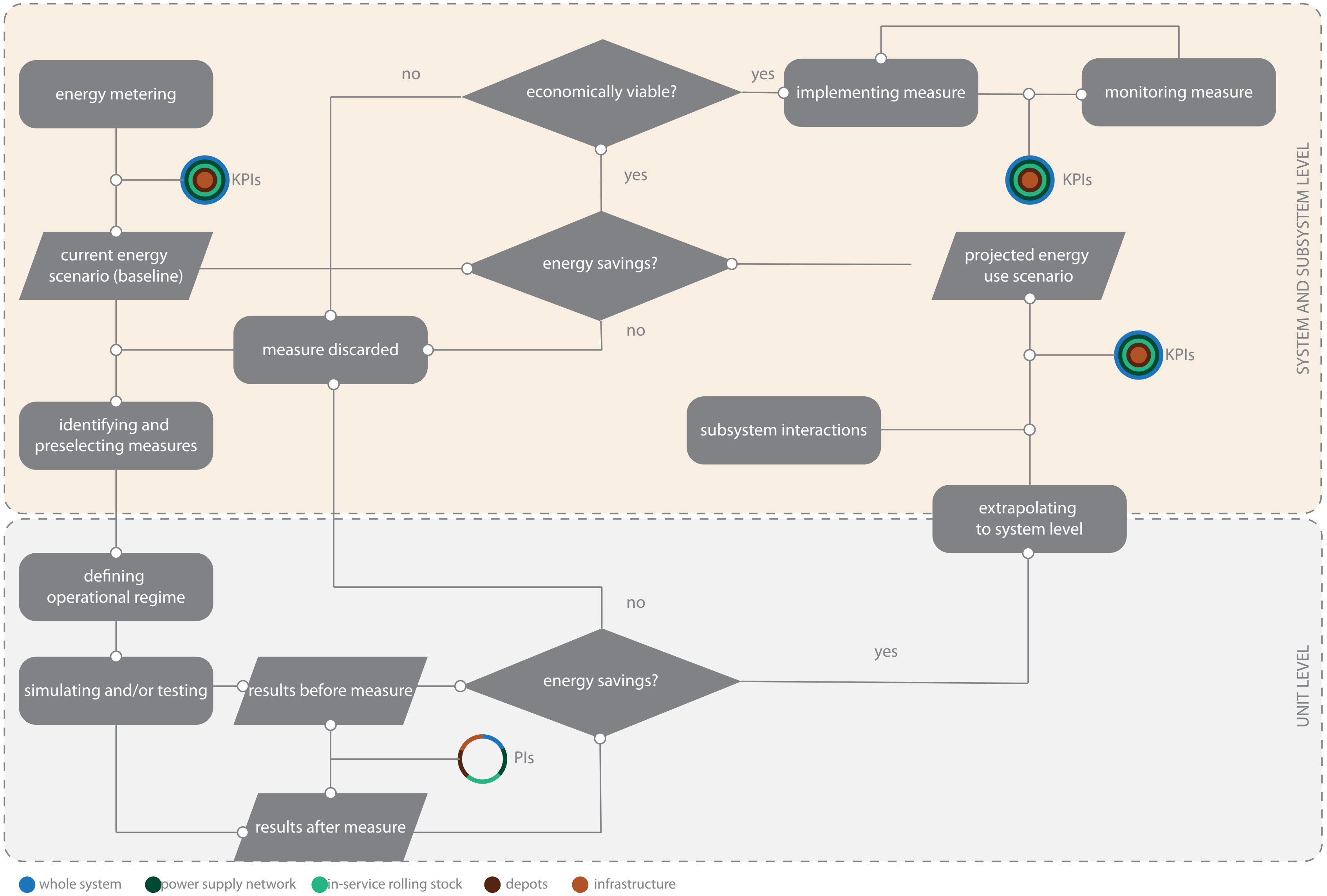

Figure 29. Schematic representation of the operationalised framework using KEPIs to deploy interventions aimed at improving energy conservation levels in urban rail systems

6.4.2.Energy efficiency measures and framework

The proposed KEPIs-based framework has been structured in such a manner that KPI_{01} and KPI_{02} would respectively account for the reduction in CO_2 emissions and the energy savings produced at system level by any measure (see Figure 28). However, establishing the effect of those measures and interventions on different subsystems is also crucial when developing optimal energy efficiency strategies. To illustrate further the use and operational aspect of the proposed framework, Table 26 shows the applicable, most relevant KEPIs for the evaluation of a portfolio of energy conservation measures typically available in any given urban rail system as analysed and discussed in detail in Chapter 5. In addition to linking the main KPIs associated with each measure, the table also shows which additional KPIs would reflect the secondary effect of that particular measure on other subsystems. For instance, interventions aimed at minimising 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 (KPI_{07} and KPI_{10}). Furthermore, the use of regenerative braking technologies, together with the application of eco-driving techniques and driver advisory systems (DAS), would shave off power peaks in the line (Malavasi *et al.*, 2011; Lu *et al.*, 2014) and consequently reducing the distribution energy losses (KPI_{05}). It should also be considered that improvement of the vehicle comfort functions could mean significant mass increase, thus increasing the traction energy consumption (KPI_{06}). In addition to the measures listed in Table 23, there is a group of interventions (e.g. generation of renewable energy and the recovery of waste heat) seeking to increase the system's energy self-sufficiency and reducing its associated CO_2 emissions rather than aiming at reducing the system energy consumption. The effects of such interventions would not be directly reflected by KPI_{02} (specific energy consumption) but by KPI_{01} (Specific CO_2 emissions). The increase in the share of renewable energy would be covered by KPI_{03}, whereas the recovery of waste heat would be registered by KPI_{04}.

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

Table 26. Summary of energy saving measures for urban rail systems and their relationship with the proposed KEPIs-based monitoring framework

6.5. Chapter conclusions

This Chapter 6 has integrated the results of Phases 01 and 02 of this thesis as part of the third and final phase (Phase 3) to define an adaptable systemic monitoring framework architecture based on a hierarchical sets of thermodynamic and physical-thermodynamic key energy performance indicators (KPIs), performance indicators (PIs) and parameters (Ps) all of which have been collectively termed KEPIs. Given the complexity of urban rail 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: i) a multilevel analysis of the actual energy performance of the system; ii) an assessment of potential energy saving strategies and iii) the monitoring of the results of implemented measures.

The research described in this chapter has been underpinned by a mainly inductive methodological approach that has included a validation process through structured consultation with stakeholders to guarantee a meaningful outcome. This has resulted in the detailed definition of a holistic framework architecture centered in a set of twenty-two indicators and four parameters created at three different levels i.e. ten key performance indicators to establish the energy performance of the whole system and complete subsystems, twelve performance indicators to evaluate the performance of single units within systems (e.g. a train as part of a fleet) and four parameters capturing data complementing the KPIs and PIs. This novel monitoring framework architecture and its comprehensive operationalised description represents a methodology through which the energy performance of urban rail systems can be compared and contrasted leading to the improvement of energy conservation levels.

This monitoring framework based on a set of KEPIs and associated implementation methodology constitutes the necessary basis of a complete decision-support tool for the optimisation of energy usage in urban rail systems. It is intended for monitoring, assessing and informing the relevant stakeholders using the framework concerning the deployment of interventions resulting in energy optimisation of urban rail systems. The conditions that determine such energy consumption are unique to each and every urban rail system. Characteristics such as topography, service levels, timetable, operational strategies, rolling stock, and driving style all contribute in different proportions to the overall energy used in each system. The proposed framework is valid for all types of urban rail systems having a flexible and adaptable nature.

This last aspect has been carefully considered in its development allowing users to select those parameters relevant to the particular characteristics of their given system, as well as introducing additional indicators that might be more suitable than those included in this chapter. To complete the validation process, Chapter 7 describes in detail the outcomes resulting from the implementation of this framework in five different urban rail systems, illustrating its adaptability, flexibility and universality.

Chapter 7- APPLICATION OF SYSTEMIC MONITORING FRAMEWORK IN URBAN RAIL SYSTEMS

7.1. Introduction

An adaptable systemic monitoring framework has been described in Chapter 6 using a comprehensive hierarchical set of key energy-related performance indicators collectively labelled KEPIs enabling i) a multilevel analysis of the actual energy performance of the system, ii) an assessment of potential energy optimisation strategies and iii) the monitoring of implemented measures. The outcomes presented in Chapter 6 have been validated though structured stakeholder consultation. Additional to this, it is considered necessary to provide an illustration of the operationalised aspects of the framework to complement and complete the validation procedure. This chapter aims to address this by discussing the framework execution process as performed by stakeholders representing five urban rail systems with different characteristics aiming to cover the three aspects described above. This has been done by means of five application cases whereby stakeholders[15] (i.e. public transport authorities, operators and equipment manufacturers) have been given the framework and its KEPIs to assess a selection of technological and operational measures aimed at optimising energy performance. Due to confidentiality issues, actual consumption figures have only been provided in the context of the measures assessed in these five cases.

Specifically, section 7.2 describes the methodological characteristics common to the five application cases. Section 7.3 defines the cases in relation to the three core aspects of the framework, discussing the characteristics of the five urban rail systems considered as well as the outcomes following the implementation of the framework, while section 7.4 provides the conclusions for the chapter.

7.2. Methodological aspects

As specified in previous chapters, Phase 3 of the thesis (Chapters 6 and 7) combines inductive and deductive methodological aspects to define and develop a holistic, hierarchical framework architecture and corresponding operationalised structure. Chapter 6 outlined the constructive consultation process followed for the development of the framework and the KEPIs in particular (see Figure 28 and Figure 29 plus section 6.2). This process has also been applied to illustrate the execution aspects in relation to the framework schematic (Figure 29), as detailed in Figure 30. Inductive methodological aspects are represented by the data collected during the application cases and their analysis drawing conclusions on suitability of measures and indicators.

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[15] This part of the research has been completed in the context of the research grant No FP7-284868

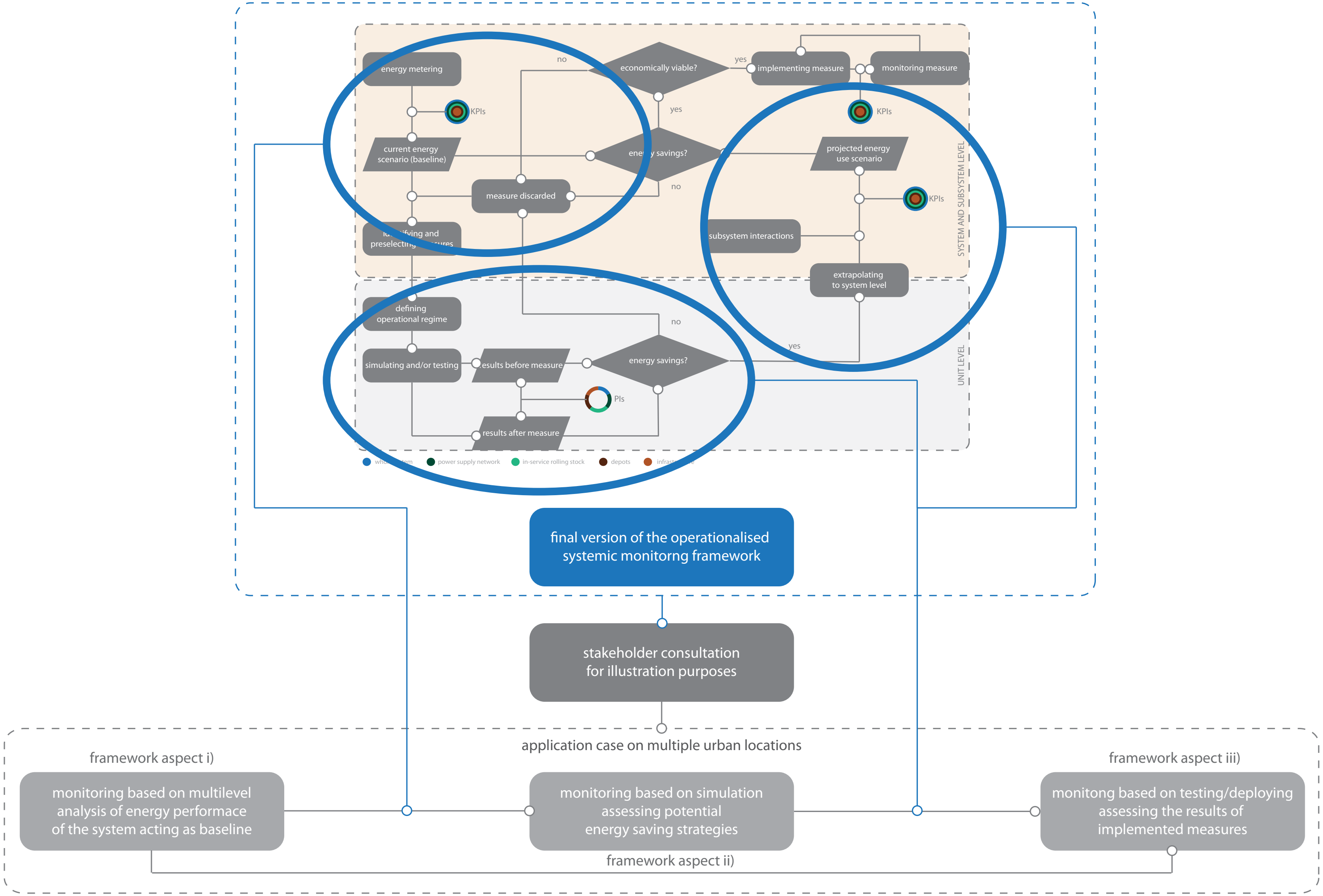

Figure 30. Schematic representation of the approach followed to illustrate the operationalised execution of the systemic monitoring framework

7.3. Application of the systemic monitoring framework to five urban rail systems

7.3.1. Introduction

To illustrate the practical aspects of executing the systemic monitoring framework proposed in this thesis, five application case studies have been carried out aiming at assessing the three core aspects of KEPIs (se above). At the core of this process are a selection of three technological and eight operational measures that have been assessed by a multinational stakeholder group from five different urban rail systems using the framework and KEPIs (Chapter 6). Table 27 summarises the measures assessed.

ID	Name	Brief description	Domain/area
TECH_01	New auxiliary converter	Novel concept of an auxiliary converted based on the use of silicon carbide low losses components (transistors) able to provide reduced energy consumption	Rolling stock (in-service and stabled)
TECH_02	On-board energy storage system	Li-ion batteries to capture regen braking energy and fast short charge capability	Rolling stock (in-service)
TECH_03	Heat pump for technical rooms	Novel free-cooling system for technical equipment rooms in underground urban railways using water-based ground sourced exchange.	Infrastructure (tunnels)
OP_01	Zoning for improved fan control	Developing distinct zones (zoning) in stations aiming at improving the control strategies for fan systems by separating the platform and concourse areas	Infrastructure (stations)
OP_02	Lighting strategies for stations	Strategy aiming at striking a balance between optimised use of energy and provision of high quality illuminated station areas	Infrastructure (stations)
OP_03	Escalator operation strategy	Strategy aiming at optimising operation of station escalators using a combination of variable speed and switching off at selected off-peak periods	Infrastructure (stations)
OP_04	Escalator energy optimisation	Strategy seeking to assess the potential of using regenerative energy from downward moving escalators	Infrastructure (stations)
OP_05	Fan control strategies for technical rooms	Measure based on the introduction of control strategies for cooling fans in technical rooms for optimal operational temperature and energy usage	Infrastructure & Depots
OP_06	Temperature requirements in technical rooms	Measure aiming to identify the optimal thermal conditions required for the correct functioning of technical rooms, particularly those housing ESSs	Infrastructure & Depots
OP_07	Lighting strategies for technical room clusters (e.g. corridors)	Strategy introducing sensors and time-depended relays in technical corridors for reduced energy consumption	Infrastructure & Depots
OP_08	Switch off tunnel illumination	Measure to reduce the energy consumption in tunnels by switching off permanently illumination in tunnels leaving only emergency lights on	Infrastructure (tunnels)

Table 27. Technological and operational measures assessed as part of the five application cases

These five application cases were carried out using the core stakeholder group involved in the consultation process discussed in section 6.2. Table 28 provides an overview of the measures assessed by each organisation and urban location.

City	Stakeholder type	Measure(s) directly tested	Measure(s) estimated
Milan	Public transport authority and urban rail systems operator (underground metro)	TECH_01	OP_01 OP_02 OP_04 OP_05 OP_07 OP_08
	Equipment manufacturer (component)		
Vitoria-Gasteiz	Public transport authority and urban rail systems operator (tramway)	TECH_02	
	Equipment manufacturer (Battery)		
	Equipment manufacturer (vehicle)		
Rome	Public transport authority and urban rail systems operator (underground metro)	TECH_03	
	Equipment manufacturer (technical room)		
Paris	Public transport authority and urban rail systems operator (underground metro and suburban)	OP_02 OP_03 OP_04 OP_06 OP_07 OP_08	OP_01
	Expert (Systems integrator)		
Istanbul	Public transport authority and urban rail systems operator (underground metro)	OP_01 OP_05	OP_02 OP_04 OP_07 OP_08
	Expert (academic adviser)		

Table 28. Application cases participants and their role

The application of the framework and associated methodology is based on a common structure of eleven different technical and operational interventions applied to five urban rail systems, each with its unique characteristics. Figure 31 represents the overall structure followed.

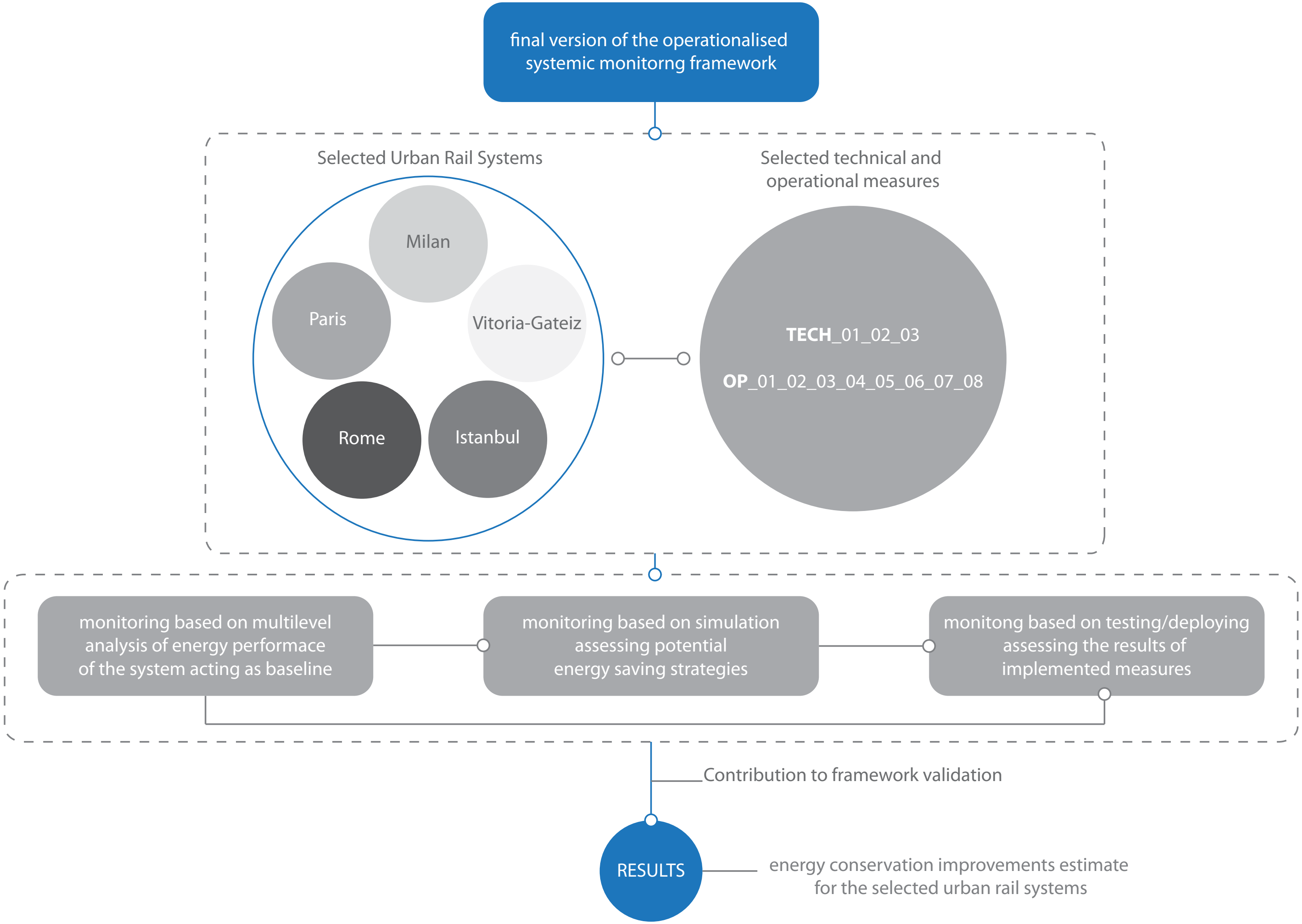

Figure 31. Overall structure followed to illustrate the execution of the framework to five different application cases

The focus of these five application cases is to illustrate the flexibility, adaptability and operationalised aspects of the proposed framework and associated KEPIs and in particular its three key aspects, namely enabling i) a multilevel analysis of the actual energy performance of the system, ii) an assessment of potential energy optimisation strategies and iii) the monitoring of implemented measures. Table 42 and Table 43 in section 7.4 summarise the overall results provided following the implementation of the application case in the five urban rail networks involved.

7.3.2. Monitoring based on a multilevel analysis of the actual energy performance of the system

In order to assess the capability of the holistic monitoring framework to provide a global energy performance record of the system acting as a baseline, the representatives of the five urban locations carried out an internal assessment based on the KEPIs and specifically chose KPI_{02} *specific energy consumption* as the KEPI that suited best this aim. Figure 32 shows the section of the operationalised framework used in this approach.

The feedback provided by the five application cases during activities related to the multi-level analysis of energy performance suggested that as different urban rail systems have different approaches to measure energy consumption it is not always possible to obtain a clear single figure for global specific energy usage (KPI_{02}). As a result, and while acknowledging and accepting the suitability of KPI_{02} given that these organisations and individuals were also involved in the consultation process defining the KEPIs, they proposed a modification of this KPI to suit this particular application exercise. Specifically, it was proposed that the global energy performance of the system was measured in three different ways, namely i) total energy consumed by the system in relation to the total number of passenger-journeys using the system in one single year (KPI_{02a}) ii) total energy consumed by the system in relation to the total number of seats-km offered by all of the trains in the system per one single year (KPI_{02b}) and iii) total energy consumed by the system in relation to the total distance covered by all the trains the system in one single year (KPI_{02c}). The passenger-journey metric is understood as the number of single origin-destination trips made within the system over the period of time considered. This is in line with the international practice as defined by independent bodies e.g. the Organisation for Economic Cooperation and Development (OECD) and the Inter-secretariat Working Group on Transport Statistics – Eurostat, European Conference of Ministers of Transport (ECMT), United Nations Economic Commission for Europe (UNECE) (OECD, 2002).

The feedback also proposed considering selected lines as the *whole system* in this particular case. This was due to practical aspects e.g. availability of data as well as for consistency of approach so that the technological and operational measures can be compared at different urban locations. Chosen lines and locations included Milan’s line 3 (L3), Paris’ line 14 and RER A, and Rome’s Barberini Metro station.

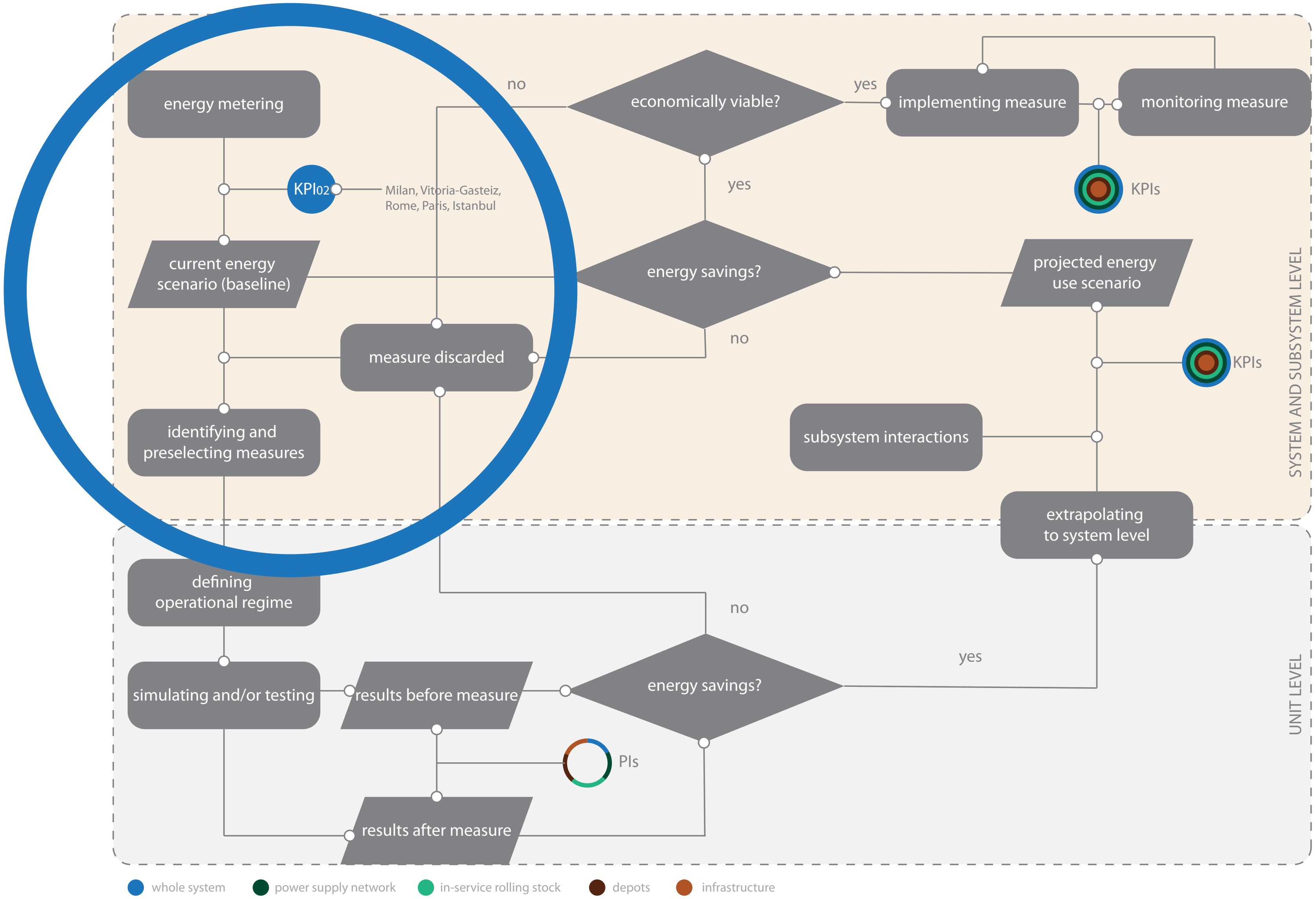

Figure 32. Section of the operationalised holistic monitoring framework used to assess enabling aspect i) a multilevel analysis of the actual energy performance of the system.

7.3.3. Monitoring based on potential energy saving strategies

A set of eleven measures (three technological and eight operational) as indicated in Table 27 and Table 28 have been used by the five different urban rail systems to illustrate the execution process of the holistic monitoring framework. Based on these and the data available (either by direct measure or by calculation) the stakeholders representing the five urban rail systems decided to use KPI_{02a}, KPI_{02b}, KPI_{02c}, KPI_{05}, KPI_{06}, KPI_{07}, KPI_{08} and KPI_{10} as the most representative indicators allowing them to assess the energy savings potential of the technical measures considered plus KPI_{02a}, KPI_{02b}, KPI_{02c} and KPI_{10} for the operational measures. In addition, the interdependencies of these KPIs with corresponding PIs were also identified and used for calculation purposes. Specifically, the participants decided to use PI_{03}, PI_{04}, PI_{05}, PI_{06}, PI_{07}, PI_{08}, PI_{09}, PI_{10}, PI_{11} and PI_{12} although for confidentiality reasons the actual values of PI_{05}, PI_{10} and PI_{11} were not shared. The use of these PIs is consistent with the identified interdependencies discussed in Section 6.3.3 (e.g. Figure 28). Similarly to the previous step, some KPIs were generated to complement the way information was provided and obtained for this particular case study. KPI_{06} *in-service traction energy consumption* was split into two complementing indicators, KPI_{06a} measuring the in-service traction consumption per passenger-journey (instead of passenger-km) and KPI_{06b} measuring the in-service traction usage in relation to the service capacity offered in the system. KPI_{07} *in-service auxiliaries energy consumption* was also split into two complementing indicators, KPI_{07a} and KPI_{07b} both using the same pattern i.e. consumption per passenger-journey and capacity on offer respectively. Regarding PIs, the Rome stakeholders decided that the technical measure deployed (TECH_03) required a specific indicator related to refrigerating systems, which led to the definition of a new indicator P_{13}. This indicator measures the energy efficiency ratio (ERR), a widely used parameter for cooling systems. Figure 33 shows the section of the operationalised framework used.

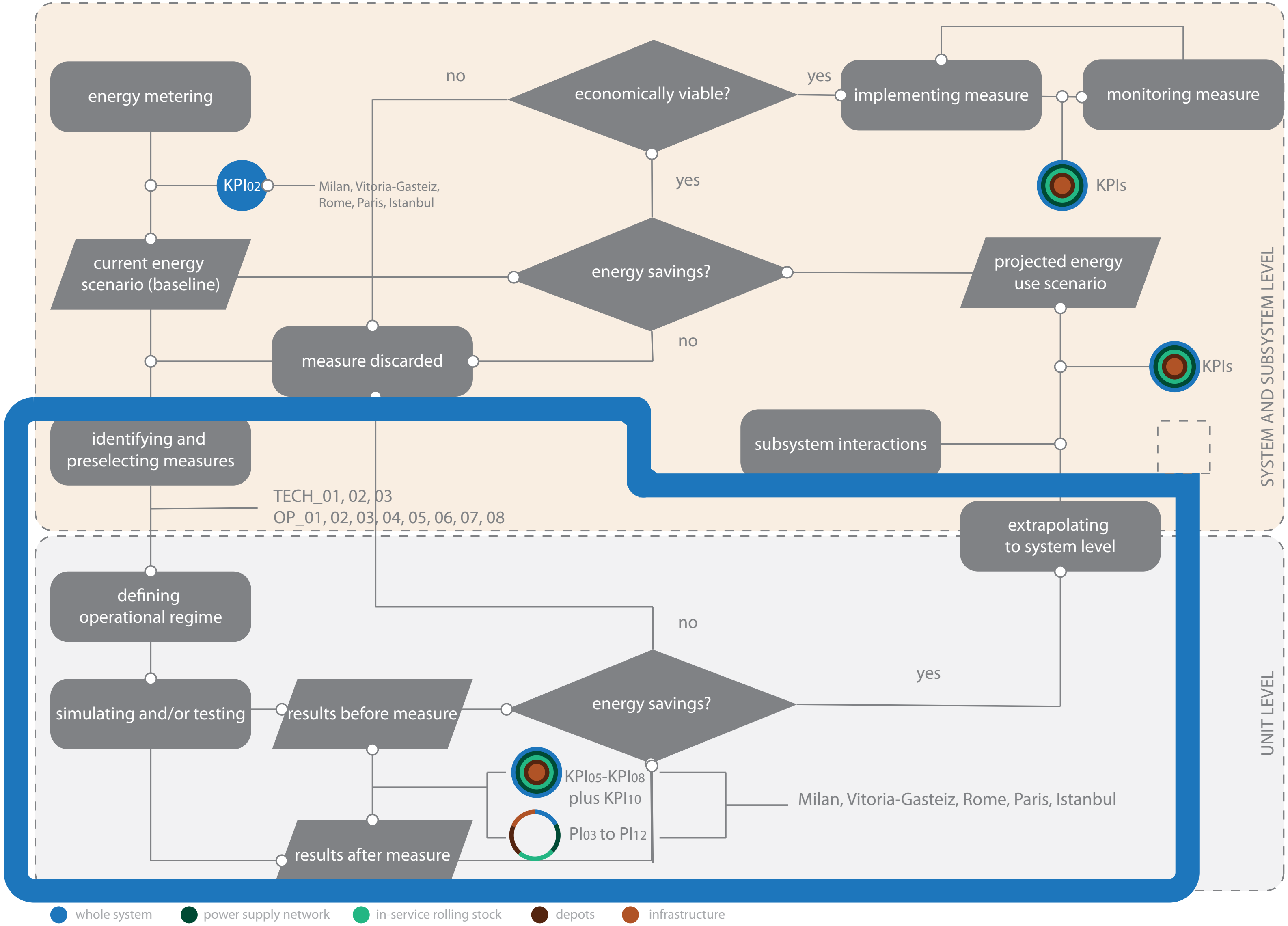

Figure 33. Section of the operationalised holistic monitoring framework used to assess enabling aspect ii) an assessment of potential energy optimisation strategies.

7.3.4. Monitoring based on results from implemented measures

This third aspect of the framework aims to allow the continuous monitoring of deployed interventions. Logically, the longer the monitoring period, the better the data generated and the more interesting the conclusions that can be drawn. However, for the purpose of these five application cases, the eleven measures implemented were monitored for a limited period of up to a year. In addition, the outcomes of the in-situ implementation (section 7.3.3) were extrapolated to the other locations to assess the potential of these measures on other systems e.g. TECH_01, TECH_02 and TECH_03 were physically tested on Milan's Metro Line 3, Vitoria-Gasteiz tram network and Rome's Barberini Metro station respectively and their performance extrapolated to the Paris and Istanbul whole systems. Similarly, the operational measures explored in Paris and Istanbul were used to consider their potential impact on Milan's system. The KPIs and PIs selected were the same as those indicated in section 7.3.3. Figure 34 shows the section of the operationalised framework used to assess this particular aspect i.e. monitoring of deployed interventions.

In addition to the energy optimisation evaluation of the proposed measures the framework also accounts for financial considerations, which are essential in this type of decision-making process. The application cases have considered the potential economic viability of the three technical measures based on payback estimation per technology and location. Other aspects considered by the stakeholders were the applicability of the solutions e.g. new systems only or retrofitting, potential research and development implications of the technology and the estimated time to market. However these considerations are out of the scope of this thesis, as they are not directly related to the development of neither the holistic monitoring framework nor its execution.

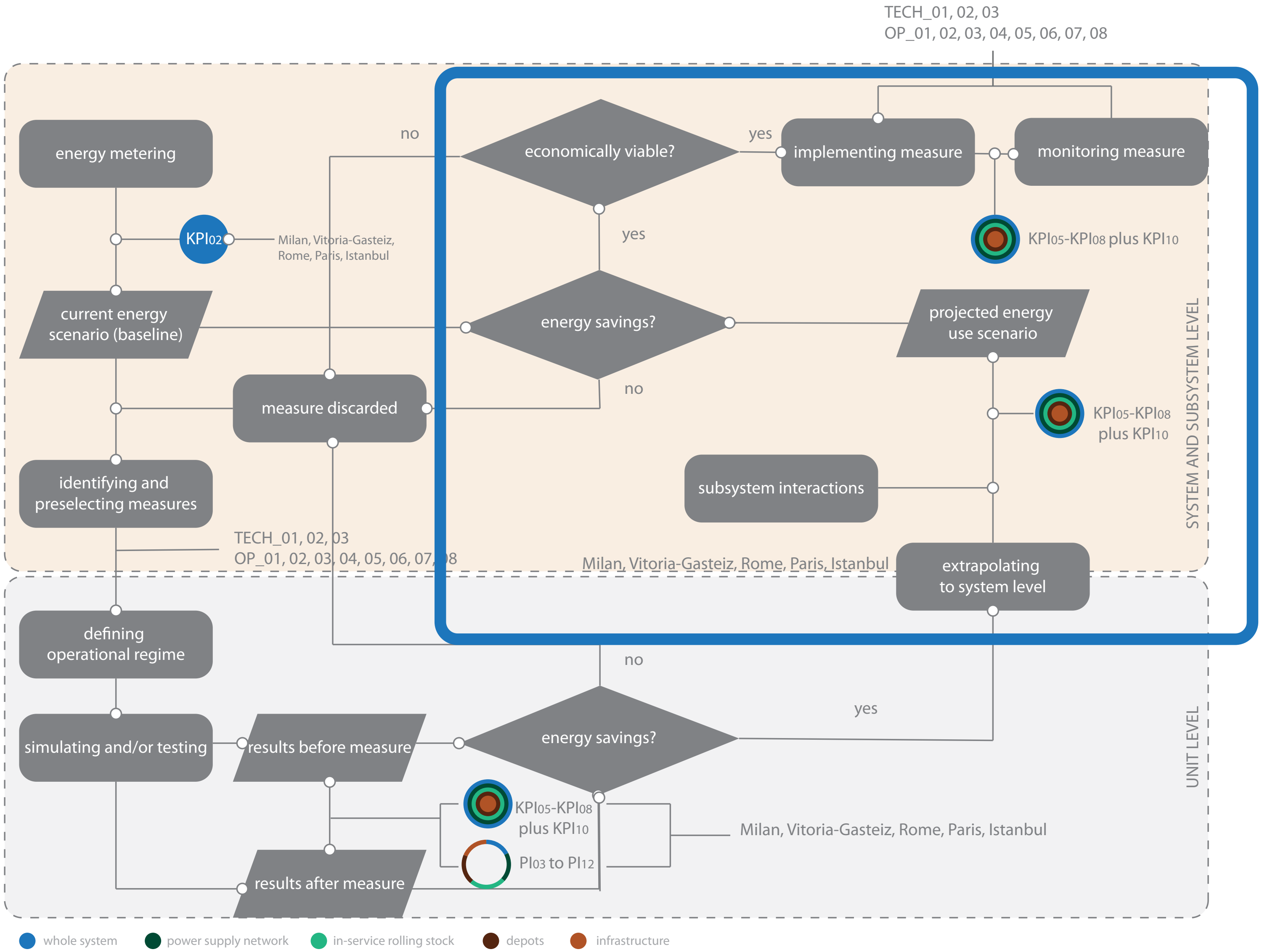

Figure 34. Section of the operationalised holistic monitoring framework used to assess enabling aspect iii) the monitoring of implemented measures.

7.3.5. Selected urban rail systems characteristics

As indicated in previous sections of this chapter, stakeholders from five urban rail systems have applied the systemic monitoring framework and associated methodology in order to illustrate its execution by investigating the energy saving effects of implementing a range of eleven technical and operational measures in their own systems. In doing so, this procedure complements the validation process performed during the consultation process described in Chapter 6. The main characteristics and involvement of these five systems is detailed below based on information provided by the stakeholders responsible for each urban rail system.

Milan

The urban rail system in Milan combines five urban (M) and thirteen suburban (SB) lines. During the 2012-15 period, the metro system expanded from three lines (M1, M2 and M3) to five increasing its total length by 21% to 101.7 km. Given the lack of historical data on the new two lines, the focus of the application case was on lines M1 to M3 with particular emphasis on M3. These three lines are operated by eight different types of rolling stock totalling 152 trains with installed power ranging from 1,520 kW in so called type 2 and 3 rolling stock running without air conditioning on line M1 to 2,780 kW in the more modern *Meneghino* units. Line M3 is operated by 45 trains powered by overhead catenary at 1,500 V DC serving 21 stations.

As indicated in Table 28, the Milan urban rail system deployed and monitored an intervention based on a novel concept of auxiliary converter (TECH_01) installed on one of the two traction units of a vehicle servicing its line M3. Specifically, a novel silicon carbide MOSFeT (Metal Oxide Semiconductor Field effect Transistor) converter was deployed replacing existing silicon IGBT[16] converters. These devices are used to control the amount of energy flowing to the traction unit including the capability of switching on and off. The main expected advantage of this novel technology (TECH_01) is its reduced losses in the region of 1.7 times when compared with the converters being replaced (Osiris, 2015).

In addition to TECH_01, the effects on energy consumption in Milan's system of the following operational measures were calculated both at sub-system and system level using the corresponding KPIs and PIs as defined in the monitoring framework:

- Zoning for improved fan control on stations (OP_01);
- Improved lighting strategies for stations (OP_02);
- Escalator energy usage optimisation (OP_04);

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[16] Insulated gate bipolar transistor (IGBT)

- Fan control strategies for technical rooms (OP_05);
- Lighting strategies for technical room clusters in tunnels and deports (OP_07);
- Switching off tunnel illumination (OP_08)

Stations in the M3 line were used for this assessment. Regarding stakeholders involvement, this application case included the participation of the public transport authority and urban rail operator and the auxiliary converter manufacturer and rolling stock manufacturer.

Vitoria-Gasteiz

This city in northern Spain represents a smaller surface urban rail system interacting with other transport infrastructure. Specifically, Vitoria-Gasteiz operates a modern tramway system, which began operations in 2008. It comprises two lines over a total network length of just under 13 km serviced by one single type of rolling stock powered by overhead catenary at 750 V DC and with a rated power of 480 kW per vehicle.

This tramway system deployed and monitored an intervention based on a state-of-the-art on-board energy storage system using Li-ion batteries (TECH_02) installed on a single tram. As discussed on Chapter 4 (section 4.7) this technology provides higher levels of energy and power density than other battery technologies while maintaining a relative lighter and compact overall system package. The intervention was designed to assess the possibility of reaching storage levels that would allow catenary-free operation in certain section of the network if required as well as increasing the levels of braking energy recovery by 5%. The stakeholders involved in this application case included the tramway operator, the vehicle and control systems manufacturer and the ESS manufacturer.

Rome

The rail system in Rome comprises a network of four underground metro lines (A, B, B1 and C), six tramway lines (No. 2, 3, 5, 8, 14 and 19) and eleven suburban lines (FL1 to FL8, ROMA Lido, ROMA Viterbo and ROMA Giardenetti) covering the whole metropolitan area.

The focus of this application case was on applying the monitoring framework and associated methodology to assess the potential energy saving benefits provided by the deployment of an intervention using a novel free-cooling system (TECH_03) for technical equipment rooms situated underground. To be able to use such technology, access to suitable underground water e.g. a well or a stream is a *sine qua non* condition. The Barberini Station on the metro line A was selected as the ideal location for this intervention given its access to a local well with the necessary supply of water. The free-cooling technology is based around the basic heat-exchange principle whereby the water temperature is lower that the ambient temperature in the targeted area (technical room in this case). The Barberini well is located 12m deep with a water temperature between 10° and 15° C. The temperature in the technical room can reach very high levels given the climatic conditions in Rome and the lack of ventilation, with a mean annual temperature in this specific technical room of 29° C. The intervention aimed to maintain the room at a temperature around 22° C.

The stakeholders involved in this Roman application case were the public transport authority and urban rail operator together with the equipment manufacturer.

Paris

The urban rail system covering the Paris metropolitan area is one of the largest and busiest networks in the world. A recent report from the international association of public transport (UITP, 2015) indicated that Paris is the one of only twelve urban systems in the world with over 200 km of lines. The report also specified that the system has a high level of patronage reaching 1.5 billion passenger-journeys per year, the largest in Europe and tenth in the world. The network comprises sixteen metro lines (M1, M2, M3, M3bis, M4, M5, M6, M7, M7bis, M8, M9, M10, M11, M12, M13 and M14), eight tramway lines (T1, T2, T3a, T3b, T5, T6, T7 and T8) and four suburban lines (RER[17] A, B, C and D).

The potential effects on the Paris network of the three technical measures (TECH_01, TECH_02 and TECH_03) deployed in Milan, Vitoria-Gasteiz and Rome respectively were assessed using the monitoring framework proposed. Specifically, those results were interpreted and adapted to the complete metro network (TECH_01), the complete tram network (TECH_02) and 291 suitable locations (stations and tunnels) on the whole metro network. As indicated previously, these locations must have access to suitable underground water reservoirs e.g. a well.

Regarding operational measures, the Paris application case assessed the following interventions using the proposed framework:

- Zoning for improved fan control on stations (OP_01);
- Improved lighting strategies for stations (OP_02);
- Escalator operation strategies (OP_03)

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[17] *Réssau Express Régional*

- Escalator energy usage optimisation (OP_04);
- Assessment of temperature requirements in technical rooms (OP_6);
- Lighting strategies for technical room clusters in tunnels and deports (OP_07);
- Switching off tunnel illumination (OP_08)

These were assessed using the KPIs and PIs defined as part of the framework proposed and applied to suitable locations on the metro network e.g. Havre Caumartin and Bonne Nouvelle stations (M9), Place des Fêtes (M11) and the multimodal Gare du Lyon for OP_03/04.

The Paris application case has involved stakeholders representing the public transport authority and operator for the metro, tram and suburban networks with the support of expert advice from specialised systems integrators.

Istanbul

A network of six metro lines (M1a, M1b, M2, M3, M4, and M6), four tramway lines (T1 to T4) and one suburban line (*Marmaray*) over a total of 129 km of track covers the large metropolitan area of Istanbul. Extensions to lines M3, M4 and *Marmaray* as well as four new lines (M5, M7, M8 and M9) are currently under construction, signalling the rapid expansion of this network in the past 30 years. Current levels of patronage reach over half billion passenger-journeys per year. The system runs on a mix of 750 and 1,500 V DC power supplied by overhead catenary and third rail methods.

Similarly to the application case in Paris, Istanbul estimated the potential energy optimisation improvements in its network of the three technical measures (TECH_01, TECH_02 and TECH_03) deployed in Milan, Vitoria-Gasteiz and Rome respectively using the monitoring framework proposed. Specifically, those results were interpreted and adapted to the complete metro network (TECH_01), the complete tram network (TECH_02) and five suitable stations on M2 with access to suitable underground water reservoirs.

Regarding operational measures, the Istanbul application case assessed the following interventions using the proposed framework:

- Zoning for improved fan control on stations (OP_01);
- Improved lighting strategies for stations (OP_02);
- Escalator energy usage optimisation (OP_04);

- Fan control strategies for technical rooms (OP_05);
- Lighting strategies for technical room clusters in tunnels and deports (OP_07);
- Switching off tunnel illumination (OP_08)

Following a similar approach to the Paris application case, these operational measures were assessed using the KPIs and PIs defined as part of the framework proposed and applied to suitable locations on the metro network e.g Taksim station on line M2.

The Istanbul application case has involved stakeholders representing the public transport authority and operator for the metro and tram networks with the support of external experts.

7.3.6.Outcomes

The representatives of the five application cases have used the proposed monitoring framework (KEPIs) and associated methodology to illustrate its flexibility, adaptability and execution aspects by assessing how it enables i) a multilevel analysis of the actual energy performance of the system, ii) an assessment of potential energy optimisation strategies and iii) the monitoring of implemented measures. As indicated in sections 7.3.2, 7.3.3 and 7.3.4 the stakeholders involved decided to use the following KPIs and PIs as summarised in Table 29.

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Framework aspect illustrated	KEPIs			
	KPIs		PIs	
	ID	Description and remarks	ID	Description and remarks
Multilevel analysis of the actual energy performance of the system (i)	KPI_{02a}	Total energy consumed by the system in relation to the total number of passenger-journeys using the system in one single year. Adapted from original KPI_{02}.	-	-
	KPI_{02b}	Adapted from original KPI_{02}. Total energy consumed by the system in relation to the total number of seats-km offered by all of the trains in the system per one single year	-	-
	KPI_{02c}	Adapted from original KPI_{02}. Total energy consumed by the system in relation to the total distance covered by all the trains the system in one single year	-	-
Assessment of potential energy optimisation strategies (ii)	$KPI_{02a,b,c}$	As before. Used for assessment of all TECH_n and OP_n measures.	PI_{03}	In-service traction energy consumption. Used for assessment of all TECH_n and OP_n measures.
	KPI_{05}	Traction power supply efficiency. Used for assessment of all TECH_n measures.	PI_{04}	In-service auxiliaries' energy consumption. Used for assessment of all TECH_n and OP_n measures.
	KPI_{06a}	In-service traction energy consumption per passenger-journey. Used for assessment of all TECH_n measures. Adapted from original KPI_{06}	PI_{05}	Braking energy recovery. Used for assessment of all TECH_n and OP_n measures.

	KPI$_{06b}$	In-service traction energy consumption in relation to the total service capacity in the system. Per passenger-journey. Used for assessment of all TECH_n measures. Adapted from original KPI$_{06}$	PI$_{06}$	Braking energy recovery efficiency. Used for assessment of all TECH_n and OP_n measures.
	KPI$_{07a}$	In-service auxiliaries' energy consumption per passenger-journey. Used for assessment of all TECH_n measures. Adapted from original KPI$_{07}$	PI$_{07}$	Depot building energy consumption. Used for assessment of all TECH_n and OP_n measures.
	KPI$_{07b}$	In-service auxiliaries' energy consumption in relation to the total service capacity in the system. Used for assessment of all TECH_n measures. Adapted from original KPI$_{07}$	PI$_{08}$	Parked-mode vehicle energy consumption. Used for assessment of all TECH_n and OP_n measures.
	KPI$_{08}$	Braking energy recovery. Used for assessment of all TECH_n measures.	PI$_{09}$	Station HVAC energy consumption. Used for assessment of all TECH_n and OP_n measures.
	KPI$_{10}$	Energy consumption in stations and infrastructure-related equipment. Used for assessment of all TECH_n and OP_n measures.	PI$_{10}$	Station lighting and information systems energy usage. Used for assessment of all TECH_n and OP_n measures.
	-	-	PI$_{11}$	Station passenger flow-related energy usage. Used for assessment of all TECH_n and OP_n measures.
	-	-	PI$_{12}$	Tunnel ventilation energy consumption. Used for assessment of all TECH_n and OP_n measures.
Monitoring of implemented measures (iii)		Same KPIs as for assessment of potential energy optimisation strategies		Same KPIs as for assessment of potential energy optimisation strategies

Table 29. Summary of KEPIs used by the five application cases to assess the three key aspects (i, ii, and iii) of the proposed framework

The outcomes of this exercise applied to eleven energy optimisation measures on each of the five urban rail systems are discussed below.

Milan

The focus of the Milan application case was using the monitoring framework to assess the energy conservation potential following the deployment of an intervention based on a novel concept of auxiliary converter (TECH_01) installed on one of the two traction units of a vehicle servicing its line M3. The stakeholders carried out measurements on the line to determine the baseline consumption and the post-implementation consumption on the test train using TECH_01. These were also used to calculate influence of the technology on other consumptions e.g. line and system level. The outcomes provided resulting from the application of the framework in Milan are summarised in Table 30 for the technical measure TECH_01 plus Table 31 and Table 32 for the values obtained for the operational measures OP_01, OP_02, OP_04, OP_05, OP_07 and OP_08.

		KPI$_{02a}$	KPI$_{02b}$	KPI$_{02c}$	KPI$_{05}$	KPI$_{06a}$	KPI$_{06b}$	KPI$_{07a}$	KPI$_{07b}$	KPI$_{08}$	KPI$_{10}$
		kWh/pax-journey	kWh/seats	kWh/train-km	%	kWh/pax-journey	kWh/seats	kWh/pax-journey	kWh/seats	%	kWh/km
TECH_01	Baseline	0.503	0.0202	25.2	85.12	300	12.02	34.8	1.40	28.2	338
	Post-implementation	0.500	0.0200	25.0	85.09	299	12.00	32.9	1.32	28.2	336
	Differential	-0.6%	-1%	-0.8%	-0.04%	-0.3%	-0.2%	-5.5%	-5.7%	0%	-0.6%

Table 30. Summary of relevant KEPI values obtained by the Milan application case assessing TECH_01

		OP_01	OP_02	OP_04	OP_05	OP_07	OP_08	$\sum_{01}^{08} OP_{\_x}$
KPI$_{10}$	Baseline	28.7	75.5	70.5	121.9	0.2	5.3	302.1
kWh/km	Post-implementation	23.31	67.19	34.91	38.10	0.14	1.07	164.7
	Differential	-18.8%	-11%	-50.5%	-68.7%	-30%	-79.8%	-45.8%

Table 31. Summary of KPI$_{10}$ values obtained by the Milan application case assessing operational measures (OP_n)

		KPI$_{02a}$	KPI$_{02b}$	KPI$_{02c}$
		kWh/pax-journey	kWh/seats	kWh/train-km
Whole system level	Baseline	0.50	0.020	25.18
	Post-implementation	0.48	0.0194	24.23
	Differential	-4%	-3%	-3.8%

Table 32. Summary of KPI$_{02}$ values obtained by the Milan application case assessing operational measures (OP_n)

The replacement of traction auxiliary converters with state-of-the-art novel silicon carbide technology represents a modest but positive improvement in energy consumption. When assessing the potential impact at whole system level, the three variant indicators of the original KPI_{02} defined by the stakeholders i.e. KPI_{02a}, KPI_{02b} and KPI_{02c} show an average of a 0.8% reduction. Putting this into context, the stakeholders reported estimated annual energy consumption for lines M1, M2 and M3 in the region of 230 GWh. The expected savings at system level would therefore mean an annual reduction of 1.8 GWh, equivalent to the energy required to charge a fleet of approximately 975 plug-in electric vehicles (PEV) for a whole year, based on an average of 0.25 kWh per mile driven (Ipakchi and Albuyeh, 2009) and 7,383 miles per vehicle per year (Department for Transport, 2016).

The influence of this intervention on the traction power supply efficiency (KPI_{05}) is negligible (-0.04%). The traction power supply mainly comprises the substations and the power distribution network e.g. overhead catenary. This is expected, as the intervention is a vehicle component, which has no effect on the energy losses between the point of common coupling and the connection point of the power supply grid with the rolling stock on the system.

The effects of TECH_01 in optimising the in-service traction consumption vary depending on the measurement units used. The stakeholders decided to split this KPI_{06} into two different ones measuring the consumption per passenger-journey (KPI_{06a}) and per seat offered (KPI_{06b}). The results show again a modest contribution of TECH_01 in reducing these consumptions (0.3% and 0.2% respectively). The stakeholders indicated annual traction energy consumption for lines M1, M2 and M3 of circa 195 GWh. This is usually measured at the substations feeding the trains on the system which makes impossible to accurately distinguish the proportion that is actually going to power the traction units of any given vehicles and the share of in-bound energy that powers the auxiliary systems (e.g. HVAC). Nevertheless, it has been estimated that the later accounts for approximately 20% of the vehicle's consumption (González-Gil *et al.*, 2014). Therefore, it could be estimated that the annual traction-only consumption for Milan's M1, M2 and M3 is 80% of the indicated 195 GWh i.e.156 GWh meaning that the expected benefits of TECH_01 are in the region of 0.39 GWh.

The influence of TECH_01 is revealed to be most significant when assessing the savings achieved for in-service auxiliaries' energy consumption. This indicator (KPI_{07}) considers the annual usage of the auxiliaries for all vehicles in the system. As with KPI_{06}, the stakeholders decided that it would be more meaningful in this particular case to split it into two measurements estimating the energy per passenger-journey (KPI_{07a}) and per seat offered (KPI_{07b}). In any case, this assessment has resulted in similar figures for energy reduction regardless of which of these two indicators is used (5.5% and 5.7% respectively). Based on the assumptions made for KPI_{06a} and KPI_{06b} the estimated total usage for M1, M2 and M3 is 39GWh meaning that the influence on TECH_01 on this particular energy flow is approximately 2.2 GWh.

The contribution of this technological measure to braking energy recovery (KPI_{08}) is non-existent which is considered to be correct as novel auxiliary converter introduced has no effects on the braking energy recovery process.

This in-vehicle intervention has also shown a positive effect (0.6% reduction) on the energy used at stations and by infrastructure-related equipment (KPI_{10}). This is due to the higher efficiency of the technology introduced when compared with the one it replaces which translates in less thermal losses which otherwise would contribute to the temperature on stations and tunnels. This, in turn, translates into less energy required to maintain comfort levels at waiting areas and tunnels.

Regarding the six operational measures (OP_01, OP_02, OP_04, OP_05, OP_07 and OP_08) considered in Milan, the results show a range of very positive outcomes, all of which have used KPI_{10} as indicator. The more drastic of these improvements in Milan show over two thirds (68.7%) reduction in energy used to cool down technical rooms using fans and air conditioning and 79.8% reduction in the energy employed illuminating tunnels. The latter can be explained by introducing a strategy whereby only the emergency lighting is required, switching off any other tunnel lighting which otherwise would remain on constantly. Similarly, the high temperature in technical rooms due to a replacement of energy-hungry air conditioning units with more efficient units (this is based on the Paris application case, see below).

The combined effect of these six operational measures has been estimated to produce a 45.8% reduction in the energy that otherwise would be consume in Milan to power these station and infrastructure-related areas. The application case has also made use of KPI_{02} to assess the potential impact at whole system level of these operational measures resulting in an average of 3.6% reduction in energy consumption measured using the three variants proposed by the stakeholders to suit their case i.e. KPI_{02a}, KPI_{02b} and KPI_{02c}.

As an illustration of the impact potential of these outcomes, Table 33 summarises the estimated breakdown of total energy consumption of the 44 metro and 117 tram and light rail systems operating in Europe. These are based on information provided by the international association of public transport (UITP) during the consultation process and obtained from their internal database and reports. Appendix A contains a one-page summary accessed.

Therefore, considering the 175.1 GWh annual average consumption of a Metro system, the effects of the operational interventions assessed in Milan could introduce energy reduction of approximately 6.3 GWh for the average city with a metro system. Using the PEV analogy, this would be equivalent to the energy required to fully charge a fleet of 3,413 PEVs for a whole year in each of those cities.

Urban rail system type	Number of systems	Total non-traction consumption (GWh)	Total traction consumption (GWh)	Total consumption (GWh)	Average consumption per urban rail system type (GWh)
Surface/ROW B-C (Tramway and light rail)	177	705	2,787	3,492	19.7
Underground/ROW A (Metro)	41	1,516	5,664	7,180	175.1
Total (GWh)	-	2,221	8,451	10,672	48.9
Average per urban rail system (GWh)	-	10.2	38.8	48.9	-

Table 33. Summary of energy consumption estimate for European urban rail systems

Vitoria-Gasteiz

The focus of the Vitoria-Gasteiz application case was using the monitoring framework to assess the energy conservation potential following the deployment of a novel on-board energy storage system (ESS) based on Li-ion battery technology (TECH_02). This ESS was installed on one tram vehicle. The stakeholders carried out measurements on the line to determine the baseline consumption and the post-implementation consumption on the test train using TECH_02. As with the case in Milan, these measurements were also used to calculate influence of the technology on other consumptions e.g. line and system level. The outcomes resulting from the application of the framework to the Vitoria-Gasteiz tramway system are summarised in Table 34 and Table 35 for the technical measure TECH_02.

These outcomes show meaningful energy reduction resulting from using the Li-ion battery storage system on Vitoria-Gasteiz's tram with its potential impact at whole system level i.e. KPI_{02a}, KPI_{02b} and KPI_{02c} indicating an average of 3.2% reduction. Perhaps the benefits are more manifest in reducing the in-service traction energy consumption (KPI_{06a} and KPI_{06b}) where 6.5% less energy is used per unit of capacity available in the system. This is consistent with the expected contribution of such technology, which aims at capturing otherwise wasted energy to reuse it for, in this case, mainly traction purposes and therefore, reducing the vehicle's overall energy demand as described and discussed in Chapter 4.

In addition the stakeholders provided data related to the energy consumption outcomes at vehicle level using PI indicators. The most relevant of these is the combined in-service traction (PI_{03}) and auxiliaries (PI_{04}) energy consumption, which reveals a significant reduction of 13.7% as a result of using this technology on a single tram vehicle. As expected from an ESS, the braking energy recovery efficiency has been improved by 6.5% to a 94.5% level. It must be noted that the rolling stock used is less than ten years old and therefore already incorporated features that both allow for more efficient use of braking (reducing the energy waste in a first instance) as well as recovery mechanisms.

As a broad estimate and similarly to the one done based in the Milan outcomes, the potential impact on tram systems could be projected based on the 3.2% energy reduction at system level observed in Vitoria-Gasteiz. This would translate on approximately 630 MWh usage reduction per average city with a tramway system which equals to a fleet of 342 PEV cars being fully charged for a whole year.

		KPI_{02a} kWh/pax-journey	KPI_{02b} kWh/seats	KPI_{02c} kWh/train-km	KPI_{05} %	KPI_{06a} kWh/pax-journey	KPI_{06b} kWh/seats	KPI_{07a} kWh/pax-journey	KPI_{07b} kWh/seats	KPI_{08} %	KPI_{10} kWh/km
TECH_02	Baseline	0.860	0.100	25.1	91.72	657	78.6	-	-	69.9	-
	Post-implementation	0.831	0.097	24.3	91.52	630	73.5	-	-	68.9	-
	Differential	-3.4%	-3%	-3.2%	-0.2%	-4.1%	-6.5%	-	-	-1.4%	-

Table 34. Summary of relevant KEPI values obtained by the Vitoria-Gasteiz application case assessing TECH_02

		$PI_{03} + PI_{04}$ kWh/pax-km	PI_{06} %
TECH_02	Baseline	-	88.7
	Post-implementation	-	94.5
	Differential	-13.7%	6.5%

Table 35. Summary of relevant KEPI (PIs) values obtained by the Vitoria-Gasteiz application case assessing TECH_02

Rome

This application case used the monitoring framework to assess the energy conservation potential following the deployment of a free-cooling heat pump for technical rooms (TECH_03). This technology was installed on a technical room near Barberini Station on Rome's metro Line A. The stakeholders carried out measurements on the line to determine the baseline and the post-implementation consumption on this location. The stakeholders of this particular case were solely interesting in assessing this technology at sub-system level. As a result they indicated that the improvements following the implementation of this technology were a 63.3% reduction in energy consumption of tunnel ventilation (PI_{12}). Furthermore, the energy efficiency ratio (EER), a widely used indicator for cooling systems, was used as indicator to further assess and compare the performance of the proposed technical intervention with the one being replaced. The ERR expresses the cooling capacity of a system in relation to the power required as input and its inverse can be used as an indication of relative operational cost (Hausman, 1979; Kavanaugh and Rafferty, 1997). The higher the value, the more efficient the system is. The intervention in Rome defined this as a new indicator P_{13}. The outcomes provided a clear benefit in this technology for this particular location as the P_{13} value for the standard technology was 3.3 while the P_{13} value for TECH_03 was 13.7, over four times better with a power reduction of 73%.

The influence of these outcomes was explored more broadly on the Paris and Istanbul cases where multiple stations and other infrastructure interventions were assessed based on the performance of TECH_03 in Rome.

Paris

The Paris application case used the monitoring framework to assess the energy conservation potential of introducing modified operational measures applied to suitable locations on the metro network e.g. Havre Caumartin and Bonne Nouvelle stations (M9), Place des Fêtes (M11) and the multimodal Gare du Lyon connecting metro lines 1 and 14 with suburban services on RER A and D.

The stakeholders carried out measurements and calculations on the selected locations to determine the baseline and the post-implementation consumption related to OP_01, OP_02, OP_03, OP_04, OP_06, OP_07 and OP_08. These were also used to calculate influence of the measures on other consumptions e.g. line and system level. The outcomes provided resulting from the application of the framework in Paris are summarised in Table 36 for the technical measure TECH_03 plus in Table 37 and Table 38 for the operational measures.

		KPI_{02a} kWh/pax-journey	KPI_{02b} kWh/seats	KPI_{02c} kWh/train-km	KPI_{10} kWh/km
TECH_03	Baseline	0.651	0.0209	20.7	132
	Post-implementation	0.645	0.0207	20.5	91
	Differential	-0.9%	-1%	-1%	-31.1%

Table 36. Summary of relevant KEPI values obtained by the Paris application case assessing TECH_03

		OP_01	OP_02	OP_03	OP_04	OP_06	OP_07	OP_08	$\sum_{01}^{08} OP_{\_x}$
KPI_{10}	Baseline	33.4	175.7	4.8	9.5	53.1	0.2	5.2	281.9
kWh/km	Post-implementation	27.1	156.4	3.9	4.7	9	0.1	1	202.2
	Differential	-18.9%	-11%	-18.7%	-50.5%	-83%	-50%	-80.8%	-28.3%

Table 37. Summary of KPI_{10} values obtained by the Paris application case assessing operational measures (OP_n)

		KPI_{02a} kWh/pax-journey	KPI_{02b} kWh/seats	KPI_{02c} kWh/train-km
Whole system level	Baseline	0.65	0.0209	20.7
	Post-implementation	0.64	0.0205	20.3
	Differential	-1.5%	-1.9%	-1.9%

Table 38. Summary of KPI_{02} values obtained by the Paris application case assessing operational measures (OP_n)

A survey of the Paris metro network was carried out to identify locations with the necessary characteristics to potentially host and deploy TECH_03 e.g. access to cold underground water. This revealed a total of 291 stations and tunnels within the vicinity of a suitable water source at temperatures ranging from 12° C to 21° C, with 40 of the locations situated by the river Seine. Following a similar procedure to the other application cases, this suitability to deploy TECH_03 was assessed in terms of potential impact at whole system level using the three variants of the original KPI_{02} defined by the stakeholders i.e. KPI_{02a}, KPI_{02b} and KPI_{02c}. As shown in Table 36 this assessment resulted in an average of a 1% reduction of energy usage. The intervention has also shown a very positive effect (31.1% reduction) on the energy used at stations and by infrastructure-related equipment (KPI_{10}). This is due to a combination of the higher efficiency of the technology introduced when compared with the one it replaces and the suitability of the Paris metro network to deploy such technology. The former translates in reduced energy input requirements as well as less thermal losses which otherwise would contribute to the temperature on stations and tunnels while the latter has a multiplicative effect.

The Paris application case applied a higher emphasis on the assessment of operational measures using KPI_{10}. The results in Table 37 show a combined improvement in energy conservation levels of 28.3% with OP_04, OP_06, OP_07 and OP_08 indicating very high reduction levels of energy usage.

The development of different temperature zones within stations to improve the control strategies for fans (OP_01) could lead to a reduction on the energy demand of circa 19%. This strategy was based on separating the platform and concourse areas into two zones using one fan per maximum of three zones controlled by a dedicated sensor. An assessment of the lighting conditions of metro stations in Paris led to the implementation of a number of strategies to review how light is used (OP_02), yielding an 11% reduction in energy consumption. The first step involved a reduction of unnecessary lighting levels in relation with known time periods of public use areas e.g. service levels (stations closed). This was combined with updating the technology used and introducing dimmable capability so the intensity of illumination can be controlled to match public use patterns. Overall it was observed that energy used for advertising could be reduced by 2%, lighting of platforms by 7% and entry and exit areas by 2% totalling 11%.

Interventions seeking optimising the energy used by escalators (OP_03) had the potential to reduce consumption by almost 19%. The savings per escalator was measured using PI_{11} (station passenger flow-related energy usage) and ranged from 4% to 24% however, only approximately 4% of the escalators in the system met the necessary conditions e.g. gradient. Three escalators were used to explore a dual speed strategy consisting on adaptable speed based on passenger demand. These escalators were located at Havre Caumartin and Bonne Nouvelle stations (M9) plus Place des Fêtes (M11). The use of regenerative energy from downward escalators (OP_04) was applied to Gare du Lyon showing the potential to halve the energy usage. These gains are more acute during the working week with higher level of services and in locations where there is a large volume of traffic, particularly from commuting services.

The assessment of the optimal thermal conditions of technical rooms (OP_06) using KPI_{10} revealed a very significant potential in reducing energy by reviewing the thermal requirements of this type of room leading to savings of approximately 83%. Prior to the application case, technical rooms housing batteries and other similar equipment required to be kept at 17^o C while rooms housing computing equipment had a thermal target of 25^o C. Considering that these rooms tend to be underground and that the equipment housed tend to contribute to the temperature in the surroundings, achieving these targets requires significant amounts of energy. Instead, OP_06 involved revising such targets at Port d'Ivry station (serving metro line M7 and tramway T2) to measure benefits and estimate their influence over circa 200 technical rooms across the whole Parisian urban rail system. The strategy involved increasing the target temperature from 17^o C to 25^o C for the first type of room and from 25^o C to 35^o C for those housing computing equipment. This approach resulted in allowing 90% of the 200 technical rooms to use natural or mechanical ventilation instead of air conditioning systems. The Port d'Ivry intervention also explored the use of less energy demanding air conditioning using adiabatic principles (i.e. evaporation of water as heat exchange method), resulting in a high and beneficial reduction in energy demand.

A similar positive effect was noticed when assessing the KPI_{10} values generated by lighting strategies for technical room clusters (OP_07) where an approach based on traditional on-off switches was replaced by time-controlled sensors based on working practice bringing a 50% reduction in the energy consumed. Similarly, switching off unnecessary lighting in the vast network of tunnels resulted in energy savings circa 80%. However, the value of the KPI_{02} variants reveal that, once put in context, the influence of these operational measures at whole system level is far more modest with an average 1.8% energy reduction, which nevertheless for a system the size and complexity of Paris still represents savings of mega Watts hour order of magnitude. Using again the average values from Table 33 this 1.8% combined effect at system level indicated by KPI_{02} would result in approximately 880 MWh energy consumption reduction for the average city incorporating urban rail systems with right of way (ROW) A B and C. This amount of energy would be sufficient to fully charge a fleet of 477 PEVs for a whole year. Nevertheless, the consumption in Paris, one of the busiest and largest urban rail systems in the world is considered to be in excess of 1TWh per year, based on estimates by stakeholders involved in this application case and the similarities of Paris with London's underground system which has reported energy use in the region of 1TWh per year (Transport for London, 2009). Therefore, the expected 1.8% energy consumption reduction at system level translates into approximately 18 GWh saved annually or 9,752 PEVs fully charged for a whole year.

Istanbul

Similar to Paris, this application case used the monitoring framework to assess the energy conservation potential of introducing modified operational measures applied to suitable locations on the metro network e.g. Taksim Station.

Following the same common procedure of all applications cases, the stakeholders carried out measurements and calculations on the selected locations to determine the baseline and the post-implementation consumption related to OP_01 and OP_05 as well as estimating the influence of OP_02, OP_04, OP_06, OP_07 and OP_08 in addition to TECH_03. These were used to calculate the impact of the measures on other consumptions e.g. line and system level. The outcomes provided resulting from the application of the framework in Istanbul are summarised in Table 39 for the technical measure TECH_03 plus Table 40 and Table 41 for the operational measures indicated above.

		KPI_{02a} kWh/pax-journey	KPI_{02b} kWh/seats	KPI_{02c} kWh/train-km	KPI_{10} kWh/km
TECH_03	Baseline	0.647	0.0186	15.0	95
	Post-implementation	0.635	0.0182	14.7	60
	Differential	-1.9%	-2.2%	-2%	-36.8%

Table 39. Summary of relevant KEPI values obtained by the Istanbul application case assessing TECH_03

		OP_01	OP_02	OP_04	OP_05	OP_07	OP_08	$\sum_{01}^{08} OP_{\_x}$
KPI_{10}	Baseline	18.5	48.8	45.5	78.7	0.2	5.3	197
kWh/km	Post-implementation	15.1	43.4	20.5	24.6	0.14	1.1	106.8
	Differential	-18.4%	-11.1%	-54.9%	-68.7%	-30%	-79.2%	-45.8%

Table 40. Summary of KPI_{10} values obtained by the Istanbul application case assessing operational measures (OP_n)

		KPI_{02a} kWh/pax-journey	KPI_{02b} kWh/seats	KPI_{02c} kWh/train-km
Whole system level	Baseline	0.65	0.0186	15
	Post-implementation	0.62	0.0177	14.3
	Differential	-2%	-4.8%	-4.7%

Table 41. Summary of KPI_{02} values obtained by the Istanbul application case assessing operational measures (OP_n)

Following the same approach as Paris, a survey of the Istanbul metro network was carried to identify locations with the necessary characteristics to potentially to host and deploy TECH_03 e.g. access to cold underground water. This revealed only five stations and tunnels within the vicinity of a suitable water source at temperatures in the region of 13° C, none of which was near a river. Following a similar procedure to the other application cases, this suitability to deploy TECH_03 was assessed in terms of potential impact at whole system level using the three variants of the original KPI_{02} defined by the stakeholders i.e. KPI_{02a}, KPI_{02b} and KPI_{02c}. As shown in Table 39 circa 2% of energy consumption could be saved if this technology was implemented. This is a higher value than the one indicated by Paris despite having a far larger number of suitable stations (291 in Paris, five in Istanbul). A possible explanation for this apparent incongruence is the difference in size of both networks (Paris is approximately 2.5 time larger), the complexity (Paris has over four times more the number of stations) and patronage with Paris being one of the busiest systems worldwide.

The Istanbul application case also follows the Paris approach as it too applied a higher emphasis on the assessment of operational measures using KPI_{10}. The results in Table 40 show a combined reduction of energy consumption of 45.8% when comparing the baseline figures with the post-implementation readings.

The introduction of control strategies for fans in stations (OP_01) supporting a zoning approach as discussed for the Paris application case was deployed at Sisli station. This measure included installing a set of 19 sensors for controlling and monitoring energy usage purposes. This strategy was followed an introducing fan modifications similar to those at Sisli station in a further six other stations in the network. To assess this intervention, the stakeholders decided to use PI_{09} in addition to the KPIs included in the outcome tables. This showed an energy consumption reduction in some stations in the region of 34% with savings as an order of magnitude in the hundreds of kWh/m^2.

A review of the use of lighting in stations led to implementation of strategies (OP_02) similar to those applied in Paris showing alike results of energy savings circa 11%. The results related to the use of regenerative energy on escalators (OP_04) were also comparable with energy consumption reduction in the 50% region as it were the outcomes of interventions related to lighting in technical rooms (OP_07) and in tunnels (OP_08), with savings circa 30% and 79% respectively.

The assessment of fan control strategies for technical rooms (OP_05) using KPI_{10} unearthed high levels of energy waste as the measures explored indicated a potential energy saving of approximately 69%. The established approach was time-based regardless of the thermal condition in the room i.e. the fan systems would work for a pre-set amount of time irrespectively of whether the temperature in the technical room required its use. The deployed strategy involved a switch to a temperature sensor based approach whereby the fan system would only be actuated if the thermal conditions in the room required it to do so. This had a dramatic effect on consumption.

Assessing the value of the KPI_{02} variants reveal that, once put in context, the influence of these operational measures at whole system level is, as in the Paris case, less extensive but still relevant with an average 3.8% energy reduction.

7.4. Chapter conclusions

7.4.1. Summary of findings

The process described in section 7.3 has generated a set of values for KPIs (and PIs) on five different urban systems implementing eleven measures aimed at energy optimisation. Table 42 and Table 43 summarise these KPI values for the three technical and eight operational measures respectively. Both tables also display the effect of these interventions at whole system level (KPI_{02}).

			KPI$_{02a}$	KPI$_{02b}$	KPI$_{02c}$	KPI$_{05}$	KPI$_{06a}$	KPI$_{06b}$	KPI$_{07a}$	KPI$_{07b}$	KPI$_{08}$	KPI$_{10}$
			kWh/pax-journey	kWh/seats	kWh/train-km	%	kWh/pax-journey	kWh/seats	kWh/pax-journey	kWh/seats	%	kWh/km
TECH_01	Milan	Baseline	0.503	0.0202	25.2	85.12	300	12.02	34.8	1.40	28.2	338
		Post-implementation	0.500	0.0200	25.0	85.09	299	12.00	32.9	1.32	28.2	336
		Differential	-0.6%	-1%	-0.8%	-0.04%	-0.3%	-0.2%	-5.5%	-5.7%	0%	-0.6%
TECH_02	Vitoria-Gasteiz	Baseline	0.860	0.100	25.1	91.72	657	78.6	-	-	69.9	-
		Post-implementation	0.831	0.097	24.3	91.52	630	73.5	-	-	68.9	-
		Differential	-3.4%	-3%	-3.2%	-0.2%	-4.1%	-6.5%	-	-	-1.4%	-
	Paris	Baseline	0.651	0.0209	20.7	-	-	-	-	-	-	132
		Post-implementation	0.645	0.0207	20.5	-	-	-	-	-	-	91
		Differential	-0.9%	-1%	-1%	-	-	-	-	-	-	-31.1%
	Istanbul	Baseline	0.647	0.0186	15.0	-	-	-	-	-	-	95
		Post-implementation	0.635	0.0182	14.7	-	-	-	-	-	-	60
		Differential	-1.9%	-2.2%	-2%	-	-	-	-	-	-	-36.8%

Table 42. Summary of KPI values obtained from the urban rail system application cases assessing the three technological measures pre-selected.

		Milan			Paris			Istanbul		
		KPI_{02a}	KPI_{02b}	KPI_{02c}	KPI_{02a}	KPI_{02b}	KPI_{02c}	KPI_{02a}	KPI_{02b}	KPI_{02c}
		kWh/pax-journey	kWh/seats	kWh/train-km	kWh/pax-journey	kWh/seats	kWh/train-km	kWh/pax-journey	kWh/seats	kWh/train-km
Whole system level	Baseline	0.50	0.020	25.18	0.65	0.0209	20.7	0.65	0.0186	15
	Post-implementation	0.48	0.0194	24.23	0.64	0.0205	20.3	0.62	0.0177	14.3
	Differential	-4%	-3%	-3.8%	-1.5%	-1.9%	-1.9%	-2%	-4.8%	-4.7%
		KPI_{10} (kWh/km)								
OP_01	Baseline		28.7			33.4			18.5	
	Post-implementation		23.31			27.1			15.05	
OP_02	Baseline		75.5			175.7			48.8	
	Post-implementation		67.19			156.4			43.39	
OP_03	Baseline		0			4.8			0	
	Post-implementation		0			3.9			0	
OP_04	Baseline		70.5			9.5			45.5	
	Post-implementation		34.91			4.7			22.55	
OP_05	Baseline		121.9			-			78.7	

Table 42 shows that the three technological solutions have a positive, albeit relatively discreet impact on whole system conservation. The three variants of KPI_{02} indicate an improvement on overall energy consumption ranging from 0.6% to 3.4%. This is consistent with the type, scope and potential of these technologies. The lowest energy consumption improvement is provided by TECH_01, an update on a small component (converter) on board trains. In contrast, the highest differential is given by TECH_02, a Li-ion battery-based ESS, which as discussed in previous chapters has a considerable potential for contributing to energy conservation. Regarding the other KPIs, they have a wider range of values from 0.04% improvement on traction power supply efficiency (KPI_{05}) resulting from implementing TECH_01 in Milan's Line 3 to a 36.8% efficiency gap reduction in energy consumed in substations and infrastructure-related equipment (KPI_{10}) due to implementing TECH_03 in underground technical rooms of the Istanbul metro network. While this technological measure was physically tested at Rome's Barberini station, the stakeholder did not provide the information related to the KPIs calculation, hence Rome not featuring in neither of the tables summarising the results. Nevertheless, the measurements of Rome were shared with Istanbul and Paris, allowing these two urban rail systems to calculate the estimated benefits of deploying such intervention. Similarly, the gaps in the table are due to either lack of sufficient data to calculate the KPI or confidentially issues. Considering the impact of the technological measures at whole system level being measured by KPI_{02} on the application cases and projecting it to the average urban system estimates (Table 33) it is possible to suggest that: The average urban conurbation with a metro system could reduce its consumption by a range between 1.4 and 3.5 GWh annually equivalent to the energy required to fully charge a fleet of up to 1,900 PEVs for a whole year while cities with tramway systems could achieve energy reductions of about 630 MWh, enough to fully charge 342 PEVs.

Table 43 provides a comprehensive overview of the calculated KPIs for the selected operational measures. These range from a 1.5% reduction in the energy usage per passenger-journey for the combined effect of all these interventions in the Paris metro system to a 4.8% saving in the consumption per seat offered in the Istanbul system. This slightly higher performance shown by the operational measures is justifiable in a first instance by their higher number (eight) when compared with the technological interventions (three). In addition, some of these measures e.g. zoning (OP_01) and energy required for functioning of escalators (OP_04) have potentially higher relative impact, particularly in Istanbul where there is a significant number of deep stations requiring long and more energy-demanding escalators. The climatic conditions in deep stations in Istanbul also require higher energy usage for comfort functions. This difference however is more acute and evident when assessing the energy consumed in substations and infrastructure-related equipment (KPI_{10}) for the different urban systems. The combined effect of the eight measures has yielded a reduction in usage of over 45% in Milan and Istanbul and 28.3% in Paris. This can be explained by the spectrum of interventions explored in the different urban rail systems covering stations (escalators, HVAC, lighting), tunnels and technical rooms.

Similarly to the technological results outline, the gaps in the table are due to either lack of sufficient data to calculate the KPI or confidentially issues. Also, considering the impact of these operational measures at whole system level being measured by KPI_{02} on the application cases and projecting it to the average urban system estimates (Table 33) as done for the technological measures above, it is possible to suggest that the average urban conurbation with a metro system could reduce its consumption by a range between 3.1 and 6.6 GWh annually equivalent to the energy required to fully charge a fleet of up to 3,575 PEVs for a whole year.

7.4.2.Conclusions

The framework architecture of KEPIs and its implementation methodology have both been validated through a structured consultation process resulting in the contents discussed in Chapter 6. To illustrate the execution of this systemic monitoring framework and to complete the validation process, this Chapter 7 has discussed five distinct application cases involving several cities covering different types of urban rail systems (e.g. tram, metro, suburban). The complete framework (KEPIs and operationalised methodology) have been given to a group of stakeholders to allow them to implement it via assessing the potential benefits of introducing interventions based on eleven technological and operational measures. An inductive methodology has been applied to assess the outcomes. The aim of these application cases has been to illustrate the execution of the three key aspects of the framework, namely enabling i) a multilevel analysis of the actual energy performance of the system ii) an assessment of potential energy optimisation strategies and iii) the monitoring of implemented measures. All this contributes to the research objective R0_02 and research question RQ_03.

The application cases have exemplified the intended flexibility and adaptability of this holistic hierarchical monitoring framework reflected on the decision made by the stakeholders to expand some of the KPIs (i.e. KPI_{02}, KPI_{05}, KPI_{06}) for added richness of information and ease of communication in this particular case. The universality of the framework has also been illustrated. Table 42 and Table 43 show different urban rail systems opting for different KEPIs to better describe the influence of the interventions on their systems. Some of these gaps were due to lack of sufficient data to calculate the desired indicator. This, however, can also be used to exemplify these qualities (adaptability, flexibility, universality) as the framework does not only provide a systemic structured approach to energy performance and conservation of urban rail systems, but also aids to identify essential measurements that would be required if energy conservation is to be pursued. The indicators and the methodology support the identification of needed measurements underpinning the subsequent identification and pre-selection of suitable interventions.

The feedback provided by the stakeholders participating in these five application cases has been used to validate the proposed framework and operationalised methodology as it has been described in Chapter 6.

Chapter 8- CONCLUSIONS

8.1. Introduction

There is increasing significance in adopting more sustainable and clean approaches to mobility that would allow continuing the path of growth and prosperity, particularly in urban conurbations where social, economic and human interactions are magnified. Mobility, at its core, is characterised by the ability to use multiple transport modes (including rail) in a coordinated and seamless way. Environmental performance and mass transit capability should position urban rail systems at the core of a sustainable mobile society. Balancing such mobility chain towards sustainability goals requires modal shift to low energy but highly competitive modes, becoming a key challenge for railways.

The current global urbanisation growth trend is highly relevant to the contemporary sustainability agenda. Such agenda is originated predominantly from the climate change process and the necessary actions to curb it. Transport is a major aspect of this sustainability process as it is one of the most energy-consuming and polluting sectors in both developing and developed nations. Urban rail systems are regarded as an ideal solution to reduce the impact of urban mobility given their outstanding capacity, safety, reliability and environmental performance (Vuchic, 2007). However, it is imperative that urban rail systems reduce energy consumption while maintaining or enhancing their service quality and capacity (Koseki, 2010) if they are to succeed in having a prominent role in the mobility chain given the advances being made by competing modes in these areas.

The use of optimum monitoring and evaluation of energy indicators (Dincer and Rosen, 2007) is a crucial enabler to provide system control and to enhance the prospects of successful interventions pursuing energy conservation. The complexity of urban rail systems with a high volume of interrelated factors affecting energy consumption means that the selection of appropriate indicators is a challenging and critical exercise. There is a lack of consensus amongst stakeholders on how to assess energy performance of urban rail systems. This void extends to the academic literature, where the issue is largely missing. As stated in Chapter 1, the overall purpose of this thesis is to contribute to energy conservation of urban rail systems by supporting the decision-making process leading to the deployment of interventions aimed at improving energy efficiency and optimising its usage.

This chapter briefly summarises the main results of this thesis (section 8.2) and its key contributions (section 8.3) leading to an overview of proposed further work (section 8.4).

8.2. Main results

This thesis has adopted a three-phased methodological triangulation research approach to address the three research questions (RQ) derived from the two research objectives (RO) set in Chapter 1.

Phase 1 followed an inductive approach to conduct a systemic review of the literature to identify energy flows within urban rail systems that influence critical consumption patterns affecting system-wide energy conservation, performance and gap efficiency reduction. This approach has concluded that there are four main streams of energy and power usage in addition to a fifth whole systems stream i.e. power supply network, in-service rolling stock, depots and infrastructure. A Sankey diagram (Figure 8) has been created to illustrate these typical energy flows on urban rail systems, built from the collective evidence found in the literature and identifying the braking process as the most promising areas for improving energy conservation. Published research has also shown confirmation that the majority of recent advances in addressing energy optimisation have focused on in-service rolling stock primarily by using regenerative braking, applying energy-efficient driving strategies or improving traction efficiency. The significance of these approaches has been further explored by assessing management and technologies for recovery of braking energy in urban rail systems. These have shown that strategies such as timetable optimisation can yield energy consumption reduction between 3% and 14%. Similarly energy storage systems (e.g. batteries) on-board trains or installed stationary by the wayside can facilitate savings between 15% and 30%. Evidence of the lack of systemic approaches to energy usage in urban rail systems has also been found as well as a clear parallel between industrial systems and public transport systems (including urban rail) concerning energy management barriers, needs and methods used. Performance assessment in the form of efficiency monitoring and continuous consumption analysis is the basis for energy management and a critical step towards closing the energy efficiency gap. This affirms the suitability and relevance of establishing an effective monitoring framework based on indicators for enhancing conservation of energy.

Phase 2 has addressed research question 02 (RQ_02) adopting an inductive approach to enquiry about the suitability of current practice related to energy efficiency and monitoring for achieving system-wide conservation. This assessment has led to the development of a multi-layered systemic taxonomy of interventions based on five clusters of non-exclusive measures for energy optimisation usage in urban rail systems classified by type (i.e. technological and operational) and domain (i.e. rolling stock, infrastructure and whole system). These five clusters are i) regenerative braking, ii) energy-efficient driving, iii) traction efficiency, iv) comfort functions and v) measurement and management. The analysis has shown that operational measures improve efficiency of both infrastructure and rolling stock simultaneously while potentially introducing relatively minor modifications to the existing system. In contrast to this, new technologies (e.g. reversible substations) require high levels of investment and relatively major modifications to existing systems. Furthermore, an analysis of the interdependencies of the assessed interventions has been carried out together with a qualitative appraisal of their individual energy saving potential, investment costs and compatibility with existing systems. This is essential to achieve a holistic view of the energy performance of urban railways. The investigation has concluded that operational measures are usually preferred over technological interventions given the good ratio between the energy conservation potential and the level of investment required. Particularly relevant measures include optimisation of timetables based on energy requirements, introduction of more efficient control strategies for on-board comfort functions and introducing driving strategies that enhance energy conservation while fulfilling the expected service levels.

The interdependency effect of combining these three operational measures with stationary energy storage systems for maximum braking energy recovery rates could realistically lead to energy consumption reduction between 5% and 30% for existing urban rail systems where none of these interventions have been deployed previously. Nevertheless, given the high correlation between the effects of such measures and the intrinsic topographical, technical and operational characteristics of any given urban rail system, these results have to be taken as guidelines and only an in-depth analysis of each system can accurately provide the most suitable combination of measures. The latter can be facilitated by the use of a systemic monitoring framework based on a hierarchical set of indicators. To support this, a methodology has been developed applying systems analysis (Jackson, 2003) based on three key steps: i) identification of key areas for improvement; ii) identification, definition and screening of potential alternatives based on known energy flows within the system assessing their expected impact after considering their interdependencies, iii) comparison and ranking of evaluation outcomes leading to decision on suitable interventions. The principal criterion to apply this systems perspective methodology has an additional three basic aspects: i) energy saving potential of the interventions considered, ii) technical suitability and compatibility with the existing system, iii) economic viability.

Finally, Phase 3 has combined an inductive and deductive methodological approach to address research question 03 (RQ_03) enquiring about the validity of a novel systemic strategy for monitoring usage and performance leading to the conservation of energy in urban rail systems. Based on the pre-selected interventions judged to be most promising by using the methodology just described, this thesis has developed an adaptable systemic monitoring framework architecture and associated operationalised methodology. This framework includes at its core a hierarchical set of indicators allowing the monitoring of the effect and contributions of the chosen interventions in achieving energy conservation goals. Specifically, the research has defined and validated a hierarchical set of twenty-two thermodynamic and physical-thermodynamic indicators and four complementing parameters collectively termed key energy performance indicators (KEPIs). Three different monitoring levels are included in the framework governed by ten key performance indicators examining energy usage at systems level, twelve performance indicators dedicated to the assessment of single units within sub-systems (e.g. single train as part of a fleet) and four parameters capturing complementary data between the previous two levels.

The proposed framework (KEPIs, interdependencies and execution methodology) has been validated through a consultation process involving structured and semi-structured group interviews of thirty-eight representatives of different stakeholders. This framework and associated implementation methodology are intended for monitoring, assessing and informing relevant stakeholders about the deployment of intervention resulting in higher levels of energy conservation in urban rail systems. The conditions determining these conservation levels are unique to each system and include topography, service levels, operational strategies, rolling stock and driving style, all of which contribute individually and in an aggregated form (i.e. based interdependencies) to overall energy usage. Adaptability and flexibility have been carefully considered in the development of the framework allowing for the selection of the indicators that suit best the characteristics of the particular system being analysed as well as permitting the introduction of additional parameters should this be required.

Application cases have been used for illustrative and validation purposes applying the framework and operationalised methodology to five urban rail systems with distinct characteristics i.e. Milan, Vitoria-Gasteiz, Rome, Paris and Istanbul. A group of stakeholders have been given the framework and implemented it to assess the potential benefits of introducing interventions based on eleven technological and operational measures. A range of KPIs and PIs was used in each of the locations providing an interesting insight into the potential benefits of these interventions. Overall, the values of KPI_{02} *specific energy consumption* representing the global efficiency of the system were used to draw general conclusions of the potential impact of measures and consequently, the use of the framework. The effect of the three technological measures deployed indicated benefits ranging from 0.6% to 3.4% in energy consumption reduction at system level. These translate into a saving between 1 GWh and 5.9 GWh per annum for the average European metro system and approximately 118 MWh to 670 MWh for an average tramway system. In urban areas where both metro and tram systems co-exist e.g. Rome, Paris, Istanbul, London, Madrid, Milan these savings represent the energy required to fully charge over 3,500 plug-in electric vehicles for a whole year.

The outcomes of the deployment of eight different operational measures revealed potential energy usage reduction at system level between 1.5% and 4.8%. These savings mean achieving improved energy conservation levels by decreasing demand for an average metro system between 2.6 GWh and 8.4 GWh per annum. As an example, this amount of energy would be sufficient to fully charge for a whole year up to approximately 4,500 plug-in electric vehicles.

The application cases have completed the validation process illustrating the flexibility, adaptability and universality of the holistic hierarchical monitoring framework proposed depending on the individualities of each urban rail system. The outcomes of these assessment of technical and operational measures in Milan, Vitoria-Gasteiz, Rome, Paris and Istanbul have corroborated the three key aspects of the framework i.e. enabling i) a multilevel analysis of the actual energy performance of the system, ii) an assessment of potential energy optimisation strategies and iii) the monitoring of implemented measures.

8.3. Thesis contribution

The results summarised above underpin the contribution to knowledge of this thesis:

1. Understanding of energy flows in urban rail systems, identifying key subsystems and the significant relevance of the braking process;
2. A full comprehensive assessment of technologies and strategies supporting energy conservation of urban rail systems and their interdependencies;
3. A systemic methodology for implementation of energy efficiency measures in urban rail systems;
4. A detailed definition of a hierarchical set of indicators constituting the core of a systemic monitoring framework architecture;
5. An operationalised methodology for the execution of the monitoring framework supporting the appraisal of interventions aiming at enhancing energy conservation levels in urban rail systems.

This research has investigated energy usage, interventions and interdependencies that are governed by the complexity of the socio-technical system that are urban railways to develop a holistic approach based on an adaptable systemic monitoring framework and associated operationalised methodology enabling i) a multilevel analysis of energy performance of the system using a set of twenty-two hierarchical indicators and four complementing parameters, ii) an appraisal of candidate energy optimisation interventions and iii) the monitoring of the results of implemented measures.

8.4. Further work

8.4.1.Recommendations for further research

Three potential research streams can be built upon the outcomes of this thesis.

Extended detailed assessment of interdependencies

The results of Phase 2 (Chapter 5) have demonstrated the existence of interdependencies between interventions that can have positive or negative effects in achieving energy conservation. This assessment has been done largely based on information available in the literature. Given the rapid uptake of some of these technologies and strategies, further research would benefit from analysing and quantifying the combined effects of such measures in-situ for longer periods of time to uncover further synergies. This research would go beyond what the application cases have done by physically deploying multiple measures into one single system for extended time periods of at least twelve months to account for seasonal variation aspects (e.g. weather).

Unlike the application cases described in this thesis where interventions have been deployed on an individual basis in separate urban systems and their effects extrapolated to other systems, this further work would aim at deploying multiple technical and operational interventions in a single urban rail system. Specifically, the research would focus on analysing the potential synergies and conflicts at both micro level (i.e. within one cluster) and macro level (i.e. between clusters) expanding the outcomes of Chapter 5. The findings of this thesis have highlighted the high level of complexity arising from the interactions between interventions associated with the regenerative braking cluster (micro level) and between this and the traction efficiency cluster (macro level). Therefore, these two clusters should be the primary focus of any further research on this area.

Applying systems thinking and methods to this research would be needed to avoid optimising the performance of a part or subsystem without understanding the effects that might have elsewhere in the system. In particular, the suitability of implementing system dynamics theory (Forrester, 1958; 1969) and its application methodology (Forrester, 1961; 1971) should be explored. This could potentially include the development of signed digraphs and causal loops (Wiener, 1948; Jackson, 2003) as a way to visualise and analyse outcomes following the application of system dynamics methodologies for complex systems, which foresee a multiplicity of interacting feedback loops (Jackson, 2003).

Automated data gathering and analytics for enhanced framework operability

The monitoring framework proposed provides all of the necessary architecture, components and methodological approaches for its execution. This thesis has proven its validity as an enabler for making decisions regarding implementing measures for energy conservation of urban rail systems. The application cases have also shown its operationalised applicability. Building on the promising results shown in these five urban rail systems, the next step in the development of the monitoring framework would require research to explore the potential implementation of algorithms that might be suitable to better govern the monitoring process. The values obtained as part of the application cases included in this thesis have been acquired largely manually or semi-manually e.g. by extrapolating data from a range of limited available energy readings. This lengthy process requires a significant effort to compile. In order to advance the applicability of the framework and enhance its impact, further research should be conducted to assess, identify and develop suitable algorithms and strategies enabling consistent and effective data collection across the whole system, and in an automated fashion thus obviating the necessity for manual input by the framework user.

As a first step, the research should use the outcomes of Chapter 2 to further assess the current and future approaches to energy consumption data collection for each of the identified energy flows. Currently, not all of these energy streams are metered individually but are grouped together making it rather difficult to discern their separate values. Therefore, the research should conduct a detailed mapping of existing data gathering points on the system assessing how these correlate with the energy flows identified in Chapter 2 leading to the definition of a system-wide network of data gathering locations. Complementing this assessment, a review of methods and techniques for data acquisition should be performed to analyse their suitability for each of the metering points.

An in-depth analysis of data acquisition networks and associated algorithms for automatic collection of inputs would also be required. There is a significant literature covering such networks so an assessment of this body of work including its applicability to urban rail systems would be a necessary part of this future research. For instance, Heinzelman *et al.* (2000) developed a clustering approach merging data for efficiency purposes before transmitting it to a base station. Lindsey *et al.* (2002) proposed a similar improved method using chain-based protocols to reduce energy used by the sensors within the network. These and other authors also discuss potential applicable data collection algorithms related to their proposed protocols and devices, which would need to be assessed.

Future research should also consider how the proposed system-wide network of data acquisition points relates to the systemic monitoring framework as an intermediate step towards a fully integrated tool. The proposed framework (Chapter 6) constitutes the basis for further development of a comprehensive tool allowing the rationalised and systematic compilation of updates on the chosen indicators for a given urban rail system. Developing an algorithm based on the KEPIs would be necessary for the implantation of this tool. Such a tool should have off-line and on-line capability and could also be implemented on mobile devices for staff. Data visualisation would be an essential part of this research.

Systemic framework for monitoring energy performance of urban transport systems

While urban rail systems can and should aspire to be the spine of sustainable urban mobility, this cannot be seen in isolation. The outcomes of this thesis can be the basis for further research applying a systems of systems methodological approach to better understand the interdependencies that influence energy usage associated with urban mobility, regardless of the transport mode used. Specifically, the thesis has used an approach that is predominantly anchored on hard systems with an aim to improve goal seeking and viability (type A). The overarching measures of type A systems success, i.e. efficiency and efficacy (Jackson, 2003) will continue to characterise the philosophical grounding of future evolution of the framework. However, further work could expand the research by adding aspects related to both soft and hard systems e.g. considering the system as constructs (soft systems) and more relevantly, applying methodologies and techniques emerging for critical systems thinking. These two additional systems thinking approaches (soft and hard) would be required to be able to address research questions arising from the purpose of this further research. Particularly relevant and essential would be to frame the research applying inquiring systems design and cognitive mapping for strategic options development and analysis (soft systems) as well as critical systems approaches such as systems of systems (SoS) and systems of systems methodology (SoSM). The application of the latter two is paramount, as this further work would have to deal with interdependencies between highly complex systems on their own right and also linked to engagement and multiple views, all of which is aligned with the fundamentals of SoS and SoSM. Furthermore, the relevance of using SoS and SoSM resides on the nature of urban mobility, which involves a transport service offer that uses several systems each constituting a whole entity on their own right. This further work, if successful, could have profound effects in truly achieving conservation of energy in metropolitan areas leading to a significant contribution to global sustainability goals to mitigate the grave effects of anthropogenic GHG emissions and climate change. However, the complexity of the work is likely to require a sequential approach involving multiple research strands possibly linked to separate projects i.e. at first, conceptual research should be conducted to establish the interdependencies arising from a whole systems approach to energy performance of urban transport systems. This, in turn would act as input for research aimed at developing the architecture of a system-wide urban mobility energy performance monitoring framework. Finally, this should be followed by work exploring the barriers for implementation in a given urban area.

8.4.2. Publications

A further paper is planned in addition to the three peer-reviewed manuscripts that have already been published following the research contained in this thesis (see Chapter 1, section 1.4). This paper aims at complementing the existing publications discussing the systems implications of the research as well as illustrating the viability and validity of the framework by reporting on the main outcomes of the five application cases included in this thesis.

8.4.3.Research grants

In addition to exploring funding opportunities to support the areas detailed for further research (section 8.4.1), work related to the energy efficiency topic is continuing through the recently awarded grant titled “Modelling and strategies for the assessment and Optimisation of Energy Usage aspects of rail innovation” (grant agreement No. 730827), funded by the Shift2Rail Joint Undertaking[18] of which the author of this thesis is the overall coordinator and principal investigator at Newcastle University. Findings related to Chapter 5 (e.g. technical and operational interventions) and Chapter 6 (e.g. hierarchical set of energy performance indicators) will be considered as part of that research.

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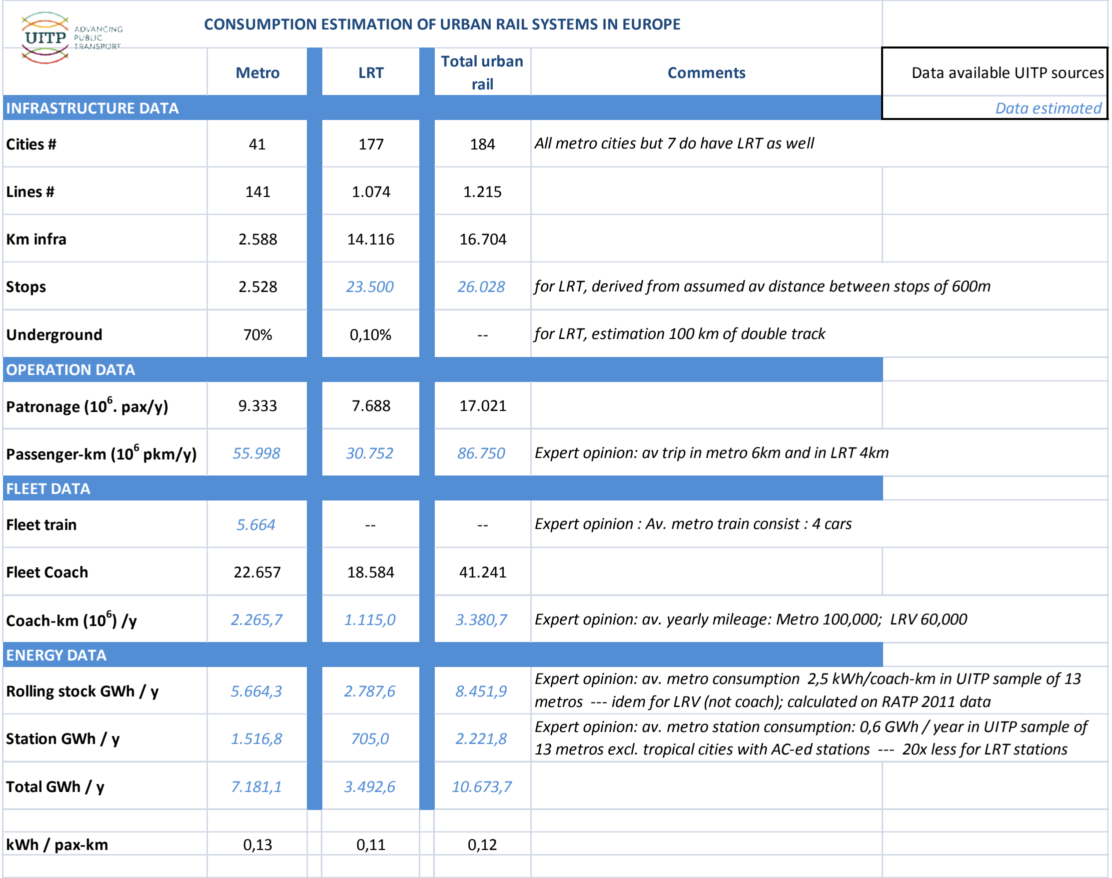
[18] http://shift2rail.org

Appendix A-Estimate of Energy Consumption of Urban Rail Systems in Europe

Table 44 contains an estimated breakdown of the total energy consumption of European urban rail systems based on internal databases and documentation held by the international association of public transport (UITP). These data sources are confidential and only available to a selected group of full members of the association. While Newcastle University has been member of the UITP since 1999 (membership No. 01655000) and currently being represented by the author of this thesis, the restrictions of the current membership exclude full access to these data sources. Therefore, the only information accessed is that included in Table 44 and provided by UITP representatives.



CONSUMPTION ESTIMATION OF URBAN RAIL SYSTEMS IN EUROPE

	Metro	LRT	Total urban rail	Comments	Data available UITP sources *Data estimated*
INFRASTRUCTURE DATA					
Cities #	41	177	184	*All metro cities but 7 do have LRT as well*	
Lines #	141	1.074	1.215		
Km infra	2.588	14.116	16.704		
Stops	2.528	*23.500*	*26.028*	*for LRT, derived from assumed av distance between stops of 600m*	
Underground	70%	0,10%	--	*for LRT, estimation 100 km of double track*	
OPERATION DATA					
Patronage (10^6. pax/y)	9.333	7.688	17.021		
Passenger-km (10^6 pkm/y)	*55.998*	*30.752*	*86.750*	*Expert opinion: av trip in metro 6km and in LRT 4km*	
FLEET DATA					
Fleet train	*5.664*	--	--	*Expert opinion : Av. metro train consist : 4 cars*	
Fleet Coach	22.657	18.584	41.241		
Coach-km (10^6) /y	*2.265,7*	*1.115,0*	*3.380,7*	*Expert opinion: av. yearly mileage: Metro 100,000; LRV 60,000*	
ENERGY DATA					
Rolling stock GWh / y	*5.664,3*	*2.787,6*	*8.451,9*	*Expert opinion: av. metro consumption 2,5 kWh/coach-km in UITP sample of 13 metros --- idem for LRV (not coach); calculated on RATP 2011 data*	
Station GWh / y	*1.516,8*	*705,0*	*2.221,8*	*Expert opinion: av. metro station consumption: 0,6 GWh / year in UITP sample of 13 metros excl. tropical cities with AC-ed stations --- 20x less for LRT stations*	
Total GWh / y	*7.181,1*	*3.492,6*	*10.673,7*		
kWh / pax-km	0,13	0,11	0,12		

Table 44. Estimate breakdown of energy consumption of European urban rail systems

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