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Research Into Options for Reducing Energy Consumption Across the Luas Network

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Research into options for reducing energy consumption across the Luas network

Eoghan Sweeney

2015

A thesis submitted to the Dublin Institute of Technology for the award of Masters of Philosophy

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Declaration

I __________________________________ declare that this thesis, which I now submit for the award of Masters of Philosophy is entirely of my own work, and has not been taken from the work of others. Any work which has been taken from others is clearly cited and acknowledged within the text.

This thesis was prepared according to the guidelines and regulations for postgraduate study by way of research in the Dublin Institute of Technology and has not been submitted in whole or in part for any other award in any other institute.

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Abstract

The aim of this research has been to identify the energy consumption requirements of the Luas network, and present practical, cost effective solutions to reducing this energy consumption. To satisfy this, Luas energy consumption data was gathered from a number of sources including the manipulation of existing Luas systems such as PS Scada, the installation of new systems including Powersoft and the specific testing of Luas rolling stock and infrastructure components. Evaluation of this data and the establishment of the Luas energy load allowed for the identification of areas where excessive energy was being consumed. New technologies, industry best practices and efficient operational procedures throughout the European light rail industry were researched and investigated to determine their feasibility for implementation on the Luas light rail network. The energy reduction solutions identified as part of this research include modifications to existing systems such as the Luas passenger saloon heating and ventilation system which has the capacity to save over 1,400,000 kWh of energy and the installation of efficient lighting technologies such as LED's and Induction lighting which would result in a saving of over 429,667 kWh of energy per year. Specific testing also took place to establish and develop optimal driving styles for Luas vehicles which has the potential to reduce total traction power by 5%. Efficient operational processes including a depot energy management process were devised and implemented during this research and have resulted in energy reductions at both Luas depots of 60%. Long term sustainability solutions such as renewable energy generation and energy storage systems were also consulted and evaluated to determine their suitability for Luas. In total the energy reduction solutions identified as a result of this research have the potential to reduce Luas energy consumption by 3,200,000 kWh, representing a 15% reduction of total Luas energy. The research results and related recommendations have been made to the research partners through this thesis.

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Glossary of Terms

ABB	ASEA Brown Boveri
AC	Alternating Current
AMP	Annual Maintenance Plan
AUP	Average Unit Price
AVLS	Automatic Vehicle Location System
CCR	Central Control Room
CCTV	Closed Circuit Television
CER	Community of European Railway and Infrastructure Companies
CFL	Compact Fluorescent Lamp
CO_2	Carbon Dioxide
DB	Deutsche Bahn
DC	Direct Current
DIT	Dublin Institute of Technology
DTI	Dublin Transport Initiative
EED	Energy Efficient Driving
EIM	European Rail Infrastructure Managers
ERRAC	European Rail Research Council
ESB	Electrical Supply Board
ESS	Energy Storage System
EU	European Union
HGV	Heavy Goods Vehicle
HVAC	Heating, Ventilation and Air Conditioning
Hz	Hertz
Ix	Illuminance

IMC	Infrastructure Maintenance Contract
kW	Kilowatts
kWh	Kilowatt hours
km	Kilometres
km/h	Kilometres per hour
ktoe	Kilotonne of oil equivalent
kV	Kilovolts
kVa	Kilovolt Amps
LCC	Luas Cross City
LED	Light Emitting Diode
LHB	High Floor Motor Bogie
LRT	Light Rail Transit
LUX	Measuring luminous flux per unit area
MET	National Meteorological Service
MIL	Magnetic Induction Light
MIC	Maximum Import Capcity
M1	Motor Car 1
M2	Motor Car 2
MRSO	Meter Registration System Operator
MW	Megawatt
OBCS	On Board Computer System
OCS	Overhead Catenary Supply
OOS	Out of Service
OPEX	Operating Expenditure
PID	Proportional Integral Derivative

PPP	Public Private Partnerships
PV	Photovoltaic
R	Measure of Thermal resistance
RPA	Railway Procurement Agency
SCADA	Supervisory Controller and Data Acquisitions System
SDCC	South Dublin County Council
SEAI	Sustainable Energy Authority of Ireland
TII	Transport Infrastructure Ireland
TWh	Terawatt-hours
U	Measure of Heat Loss through a Material
UITP	International Association of Public Transport
UPS	Uninterruptible Power Supply
UV	Ultraviolet Light
VMC	Vehicle Maintenance Contract
WESS	Wayside Energy Storage System

Chapter 1: *Introduction*

1.1 Background to the Research

The Luas Light Rail Transit (LRT) system is arguably one of the most successful capital investment projects seen in Ireland. In its eleventh year of operation, Luas is a prime example of an efficient, profitable, high quality public transport system. Luas services produced reliability and availability figures averaging 97.6% and 99.5% respectively in 2014 [1]. Light rail systems are regarded as one of the most efficient modes of transport in urban and suburban areas. Light rail operations also achieve some of the lowest emissions levels of any mass transport systems [2]. With the creation and implementation of new technologies and systems, light rail systems have the potential to further reduce their energy consumption and emission levels. Dublin Institute of Technology (DIT) in partnership with the Railway Procurement Agency (RPA) now Transport Infrastructure Ireland (TII) and Transdev supported this research in the area of energy reduction in light rail. Although this research has particular reference to the Luas LRT system in Dublin, the results and findings of this research could be applied to any similar light rail system around the world to aid in the reduction of energy consumption. In Ireland, rising costs due to inflation and declining economic activity have had a negative impact on all industries reducing sales and decreasing competitiveness [3]. Transport systems are not immune and are faced with lower passenger numbers and reduced revenues. To offset this, transport operators must reduce operational costs sufficiently. Energy is one of the principal costs associated with the operation of an electrically powered light rail system [4]. With an expanding network, Luas energy consumption has increased significantly over the past four years. Luas is now a major consumer of energy from the national grid within the urban catchment area of Dublin. The particular element of this research was conducted from 2012 to 2014. Every possible factor influencing the energy consumption associated with the operation of Luas has been analysed, with the aim of reducing this consumption. The research results, including cost benefit analysis and return on investment of potential energy reduction initiatives are recommended to the industry partners, the RPA and Transdev through this thesis.

1.2 Motivations for the Research

The primary motivations for this research were to satisfy the aims and objectives set out in section 1.1 and by doing so contribute to the international research community. Substantial literature is available in the areas of both transport and energy. There are operational initiatives such as timetable optimisation and efficient driving techniques which have been researched and presented in many forums. Significant engineering solutions also exist to reduce energy consumption. Those applicable to all industries such as efficient lighting, renewable energy generation and those specific to the transport industries such as energy storage systems to harvest regenerated braking energy are widely available throughout the academic society. Through a review of such literature it was identified that although solutions to reduce energy consumption exist there is little research available which brings together all these solutions and determines their suitability for a light rail system. This research aims to bridge this gap in the current available literature. The research is also specific to the Luas light rail system and will allow for future comparisons and evaluation of sustainability with other transport modes both in Dublin Ireland and internationally. This was achieved through the identification of Luas energy demand by means of on-site testing and energy monitoring. Industry best practices and new technologies were also consulted and analysed for suitability as an application for the Luas light rail system. Energy reduction initiatives in the form of engineering solutions and operational processes have been recommended for implementation across the Luas system, which will aid in the reduction of overall energy consumption. The results of this research have been shared throughout the research community with the publication of an academic paper, presentations and networking at both national and international conferences and through the final research results detailed in this thesis.

1.3 Aims and Objectives

The Aim of this research is to:

i). Review current literature regarding transport and energy.

ii). Conduct practical research to identify Luas energy requirements and analyse consumption.

iii). Research and present feasible and cost effective engineering and operational solutions to reducing this consumption.

The specific objectives of the research include:

i). Identify energy best practices in the light rail industry through reviewing academic literature.

ii). Establish Luas energy requirements, through manipulation of existing systems and the testing of specific Luas components.

iii). Actively monitor and analyse Luas energy consumption.

iv). Identify solutions to reduce energy; during operations, through technical modifications of existing systems and the installation of new systems.

v). Trial and test energy reduction initiatives throughout Luas operations.

vi). Determine return on investment and complete a cost benefit analysis of these initiatives.

vii). Present and recommend the research findings to the industry partners and disseminate results to the research community.

1.4 Light Rail and the Luas Network

Light rail systems are becoming increasingly popular as a solution for urban transport throughout the world. Proven to be among the most efficient modes of transport, LRT systems are the favoured mass transport solution in urban cities such as Dublin, Dubai and Melbourne [5]. The major advantages of LRT systems are accessibility and capacity compared with traditional rail, bus and car transport. The majority of LRT vehicles currently in operation are between 70% to 100% low floor, giving ease of access for passengers at street level [6]. Patronage can be as high as 8 people per meter squared standing [7]. Light rail vehicles can also reach speeds of 80 km/h on segregated sections of track. High operational frequency results in shorter journey times for traveling passengers. Rolling stock is smaller in size and lower in weight compared with traditional rail vehicles, resulting in the ability to negotiate much tighter track layouts in ultra-urban areas [8]. Luas was the first modern electrical light rail system of its kind in Ireland. Consisting of two separate lines, the Red Line was open in 2004 and now has a total of 19.5 km of track. The Green Line also opened in 2004 and incorporates 17.5 km of track [7]. The Luas network serves Dublin city centre and surrounding suburbs. During the initial planning stages, it was advised that the utilisation of such a system would be best achieved through public ownership and private operation in the form of a public private partnership. This recommendation paved the way for the Railway Infrastructure Act of 2001 to be passed and the establishment of a statutory body, known as the RPA (now TII) [9, 10]. Once established, the RPA released tenders to private enterprise for both the operation and maintenance of the system. Transdev currently operates the Luas system on behalf of the RPA. The contract which was awarded in August 2014 will expire in September 2019. Two divisions of Alstom Ireland limited hold the Infrastructure and Vehicle Maintenance Contracts which also expire in 2019 [11]. Luas operates a high frequency service, such that there is no set timetable for each tram at each stop, but rather a set interval between trams known as headways. Peak services headways are between 4 and 10 minutes and off peak are between 10 and 15 minute intervals. This type of operation requires a high volume of trams in operation at any one time, but results in the shortest travel time for passengers. The Luas system was constructed on budget at a cost of €775 million, partly funded by the Irish Government and the European Regional Development Fund. Luas currently carries in the region of 30 million passengers per annum [12].

1.5 Reducing Energy Consumption in the Transport Industry

The European Union (EU) is one of the largest economic markets in the world and the movement of people, goods and services is vital to a sustainable efficient Europe [13]. Transport is a prolific sector within the EU which must achieve sustainability, by way of reducing its energy demands and reducing dependence on imported fossil fuels. The European Commission (EC) has committed to reducing Greenhouse gas emissions to between 80% and 95% below 1990 levels by the year 2050. Some 10% of the share is expected to come from the transport sector [14]. Energy demand is expected to increase dramatically in the next twenty to thirty years [15]. By then however, it is envisioned that 90% of electricity demands will be provided by renewable sources such as wind, solar power and ocean current generation, which are all carbon neutral sources of electrical generation [14]. The European White Paper [16], produced by the EC has ten main goals to achieving a sustainable efficient transport sector. These include reducing overall emissions by 60% by the year 2030, increasing the rail freight share by 30% and tripling the EU rail network, allowing for the majority of medium distance transport to be made by rail [16]. Organisations and groups such as the Community of European Railway and Infrastructure Companies, The European Rail Research Advisory Council and The European Rail Infrastructure Managers Group are actively working together to promote and lobby sustainability, reduce energy and implement the targets set out in the European White Paper and the European Energy Roadmap 2050. Initiatives such as Horizon 2020 and Shift2Rail provide funding for energy reduction research and initiates within the rail industry [17].

1.6 Structure of Thesis

The research topic, background and motivations are introduced in Chapter 1. The history of light rail in Ireland is discussed as well as an overview of the current Luas light rail system. Chapter 1 also analyses the endeavour for energy reduction within the European transport industry.

Chapter 2, presents a review of the literature in the field of transport and energy. The specific technologies and practices available to aid in the reduction of energy in light rail are examined. The operational and technical aspects of the Luas light rail systems are also described in this Chapter.

Chapter 3, describes the research methodology. The sources of data, data collection methods and analysis techniques conducted to determine the results are detailed. Obtaining accurate data on Luas energy consumption was a key element to this research.

Luas energy consumption is analysed in Chapter 4. This energy consumption analysis is split into rolling stock and infrastructure. The main factors influencing Luas energy consumption are also examined including network increases, operational changes and climatic effects.

Chapter 5, details the energy reduction initiatives which have been identified as a result of this research. Energy reduction initiatives include the modification of existing systems, the installation of new systems and changes in operational practices.

The results of the research and potential energy savings for each energy reduction initiative identified are presented in Chapter 6. A preliminary return on investment calculation is also provided in this chapter.

Chapter 7, draws conclusions and summarises the research results. The potential benefits to the Luas network are discussed. Further research required for larger scale projects are also detailed.

Chapter 2: *Literature Review*

2.1 Review of Published Literature

This literature review begins with a focus on the provision and success of light rail systems around the world. Literature available surrounding the technologies and operational aspects of energy reduction are then discussed. Finally, a review of published literature in the area of energy reduction specific to light rail is conducted.

2.1.1 Current Research in the Area of Transport and Energy

LRT systems are increasing in popularity as a solution to urban transport needs. Significant literature analyses the reasons why there has been rapid growth in the construction of LRT systems throughout the developed world. The main themes of this literature include high capacity, reliability of the service and low operational expenditure (OPEX). One of the main reasons for lower OPEX is the efficiency of LRT systems. Nevertheless, in the current western economic climate LRT OPEX must be sufficiently reduced to remain sustainable in light of great efforts made by competing transport modes to increase their sustainability.

According to the Global Light Rail Projects Report, [18] there are approximately 400 LRT systems in operation worldwide. These include the Paris Tramway, the Berlin Stadtbahn, the Yarra trams in Melbourne and the Toronto Tramway. A further 60 systems are under construction including the Doha light rail system and over 100 are in the planning stages including the Oman LRT system [19]. This highlights the growing popularity in the LRT systems as a solution to urban transport requirements. Eight of the top ten liveable cities in the world according to the Economist Intelligence Unit's Liveability survey (2014) [20] contain operational LRT systems, and the two which do not, Perth and Auckland are in the planning process for the construction of an LRT system. In fact, the most liveable city in the world as per this survey is Melbourne, which has the largest tram network in the world according to its operators Yarra Trams [21]. For a multitude of reasons such as construction cost, environmental impacts, capacity and operating costs LRT systems are the most attractive choice when identifying solutions to congestion and urban public transport issues.

Babalik [22] states successful LRT systems such as the Portland MAX have contributed to increased public transport usage, reduced car usage and as a result have improved air and noise quality in urban areas. It is systems such as the Portland MAX, that showcase the positive impacts LRT systems can have on urban areas. The research develops a methodology for analysing the success of LRT systems. Babalik [22] analyses both successful and unsuccessful systems in the form of selective case studies. There were three main section criteria's used, the first involved selecting systems which were build post 1970, the second was choosing systems which were built in urban areas which have a wide range of characteristics and the third was selecting systems which had similar political and planning approaches. The data collection approach for this research included interviews, fieldwork and document reviews. From the research it was evident that one of the main factors in the success of a LRT system is operating policies. Practices such as good connections, frequent services and effective marketing can influence the success of an LRT system. Other local operational policies including efficient driving styles or targeted door openings will aid in reduced energy losses, and increase overall efficiency and overall profitability. The Luas LRT system adopts policies such as frequent services with peak headways at less than five minute intervals. The Luas also incorporates good connections with bus, and mainline rail services at a variety of stops. These have aided in the success of the Luas LRT system.

Kim et al. [23] describes LRT systems as a means to potentially reduce congestion, energy consumption and improve air quality. The research discusses the support LRT systems have gathered from the public as a result of their high capacity and frequency which is convenient for passengers, the reliability of the service and comfort when compared to other modes of transport such as buses. The research suggests passengers tend to walk further to reach LRT stops when compared to bus transport as a result. However in the case of the St Louis Metro Link the research found through surveys that less than 10% of the LRT passengers had walked between home and the nearest station. New LRT transit systems are generally built in low density areas to reduce construction costs and allow for a permanent way to be established for the system. This is the case for the Luas Green Line which was built on the old Harcourt Main line where there are unpopulated areas of running including two stops which currently have no pedestrian access. Although this option may have resulted in lower construction costs, passenger numbers have not been what were envisioned due to a lack of investment in the area. This decision has resulted in reduced passenger numbers and as a result less revenue for the system. In this case increased pressure is placed on the system operators to sustain the service, which may be operating at a loss.

A review of current, relevant literature in the areas of light rail transport and energy suggests many solutions to reducing the overall energy consumption of a LRT system exist. Significant research has been consulted in relation to specific technical energy reduction solutions such as energy storage systems in the form of super capacitors or efficient heating systems. The Transportation Research and the Energy Policy Journals provide regular volumes with peer reviewed academic papers on both topics. This research takes a system wide approach to reducing the energy consumption of an LRT system including analysing both operational and technological aspects of possible energy reduction initiatives. This research is based on the Dublin Light rail system. It is intended that this research will provide an overall solution to energy reduction across a light rail system, and in doing so will build on previous research to contribute to the research community and ensure light rail operators have the best opportunity to reduce energy consumption across their entire network.

The Sustainable Energy Authority of Ireland (SEAI) Energy in Transport Report (2014), [24] highlights the energy demand of the transport sector in Ireland. Transport accounted for the largest primary energy demand (33%) and also the largest end user energy consumption (40%) in 2013. Public transport accounted for 5% of this consumption. In 2013, the final energy demand of the Irish rail industry fell 11.6% to 42 ktoe (Kilotonne of Oil Equivalent) when compared to 2007 figures, although the majority of this can be attributed to a reduction in heavy rail activity. Rail accounted for 1% of the total transport energy share in 2013. Although the rail share in Ireland is small, throughout the world rail transport has increased 130% since 1975 according to the Railway Handbook (2014) published by the International Union of Railways [25], and plans are to continue this growth. In 2011, 0.6% of the world’s energy consumption can be attributed to the rail industry. One of the reasons for this is the shift from diesel fuel to electrical energy. In Europe diesel usage decreased by 31% and electrical energy increased by 14%. Increasing the switch from diesel to electrical energy and with an overall reduction in energy consumption the rail industry can lead the way in sustainable efficient transport for the future.

González Gil et al [26] in research completed through Newcastle University in the United Kingdom took a holistic approach to reducing urban rail transport energy consumption. This research being the first of its kind recognised the wide range of factors which effect urban rail energy consumption and that the best approach to reducing this consumption was take a system wide approach. The methodology of this research was to first define the energy usage of the transport mode. González Gil et al [26] categorises the energy consumption into traction and non-traction energy consumption. The typical traction energy flow of urban rail systems from the power supply equates to 20% for the auxiliary load, 14% for traction losses, 16% for motion resistance and 50% for braking energy. Of the 50% for braking energy, 33% is recovered through regenerative braking and 17% is attributed to braking losses [26]. Non-traction energy consumption as categorised by this research includes the infrastructure related services which are required to operate the service. These include signalling, passengers station services etc. Through a review of both academic and industry led research the main initiatives available to reduce both traction and non-traction energy were established, these included regenerative braking, energy efficient driving, traction efficiency, comfort functions and measurement of energy consumption. By analysing the options available with respect to this list the suitability, effectiveness and investment required for each solution was established. Ultimately this research concludes that a system wide approach to reducing the energy consumption of an urban rail system is best. Before decisions to reduce energy are made a conditions monitoring process must be enacted to establish the energy demand of the system. Once established and understood solutions to reduce this energy cay be investigated. The research noted large variants in the energy consumption between the different systems and advised that the conclusions of this research should only be used as a guideline as these variants in energy consumption may be different on other LRT systems.

This thesis builds on the research conducted by González Gil [26] and the guidelines for energy reduction in urban rail. More specific energy monitoring, establishment of areas of excess energy consumption, specific testing of energy reduction initiatives will contribute to the current literature available.

Richardson [27], in research conducted through the University of Michigan analyses the sustainability of passenger transport. There are five main factors discussed in the research including fuel, access, congestion, emissions and safety. In considering the sustainability of passenger transport these dynamics and influences must be considered. For example if the system increases the kilometres operated, the fuel or energy consumed will also increase which will lead to increase emissions and will impact on safety or the potential for safety incidents to occur. When seeking to reduce the energy consumption of an LRT system all influencing factors must be considered. To modify or change one tram system or operational procedure will have an effect on another aspect of the system. An example of this may be a modification of the vehicle heating system. There may be the potential to save significant amounts of energy, but the net effect of this modification could be reduced heat in the tram. This could then lead to reduced passenger satisfaction and a reduction in passenger numbers, which will ultimately reduce revenue. In this case the savings in energy may be offset by the reduction in revenue and the overall sustainability of the system is impacted. There is a cost and benefit associated to each investment in LRT systems. When considering energy reduction investments the cost benefit analysis must consider all factors such as the impact to the passenger, overall society and sustainability of the system. The frameworks identified through Richardson's [27] research helps to ensure all factors are considered when making decisions which will inevitably determine the future sustainability of a transport system. Throughout this research the effect of the energy reduction proposals have been considered system wide.

J.P Powell [28] through University of Newcastle assessed the energy consumption of urban rail vehicles during periods of non-passengers service or when stable. With rising energy costs and growing capacity on many of the world's urban rail systems it is crucial that urban rail operators sufficiently reduce their energy consumption to remain sustainable. This research centred on the Tyne and Wear Metro system in Newcastle, England. Data was collected from energy meters fitted to one of the metro cars operating on the system between April 2012 and 2013. Analysis of the data collected led to the identification of the vehicles energy load. The total energy consumption of the vehicle during the 337 days of the trial was 515,696 kWh, the metro car travelled 130,000 km during this period. Further analysis of the operation of this metro car indicated that the hours of non-passenger service use equated to 48% of this time. The energy consumed by the vehicle during non-passenger operations or when stable was 56,059 kWh or 11% of the total power. Further analysis of the ambient temperature during the trial period indicated that the daily energy consumption was considerably higher during days where the external temperature was colder. To determine the components consuming energy while the vehicle was stable the auxiliary systems were analysed. These systems comprise of heating, ventilation, lighting, compressions and control systems. The heating system consists of two 15 kW heaters and is operated to a set temperature which is normally 21°C. The compressors drive the door actuators, suspension, and friction brakes of the vehicle. Lighting is both internal and external and is activated by push button. A review of historic temperature data in conjunction with the energy consumption of the heating system identified its consumption patterns. When the external temperature was above 12-13°C the heating system automatically switched off and its power was around 8 kW. Once external temperatures dropped below 0°C the heating system was permanently on and consuming the maximum rated power of 30 kW. The remainder of the auxiliary systems were found to have consistent energy consumption of 65%. This is made up of lighting 10%, compressors 4% and the reaming systems and control circuits 41%. The research found that the energy consumed by an urban rail vehicle when not in passenger service was not insignificant. A total of 56,059 kWh were consumed in a 337 day period which equated to 11% of the total vehicle energy consumption. Further analysis identified the heating system to be the dominant consumer of this energy. When urban rail vehicles are not operating in passenger service they are not generating revenue. In this case all efforts should be made to ensure stabled vehicles do not consume significant amounts of energy which has an associated cost. Luas has a large fleet of tram vehicles resulting in many "spare" trams being stabled in the depots each day. This thesis has assessed the energy consumed by these vehicles and presented solutions to minimising this energy consumption.

As renewable energy generation increases Lund [29] analyses renewable energy strategies for sustainable development including within the transport sector. The research focuses on Denmark as an example of a country which has had an increase in GDP of 70% but has maintained the same primary fuel consumption for over 30 years. This is due to the increased use of combined heat and power (CHP) and district heating systems. Denmark has also replaced 14% of fossil fuel consumption with renewable energy. During this period transportation and electricity consumption has increase dramatically. Lund [29] evaluates whether a 100% renewable energy system is possible for Denmark. The key aspect of sustainable development involves energy saving on the demand side, energy production efficiencies and an increase in the renewable energy generation share. The research focuses on Denmark as an example of sustainable development, where these three aspects of sustainable development have been implemented. The Danish energy authority has projected the renewable energy sources available and planned accordingly. One problem facing Denmark is the transportation sector which is fuelled primarily by oil and is expected to increase by 28% by 2020. In its analysis of a 100% renewable energy system for Denmark it is predicated that the transportation sector will replace its 20.8 terawatt-hours (TWh) of oil with 17.8 TWh of electricity, and that both battery and fuel cell technology will need to be introduced. Lund concludes that to implement sustainable energy strategies there are three main factors required; energy saving, increased production efficiencies and increased renewable generation along with a shift from fossil fuels to electricity in the transportation sector. Light rail systems are generally electrically powered however the principals of energy reduction and renewable sources of generation can be applied when adopting energy reduction strategies for light rail systems.

This thesis focuses on reducing energy in the operation of LRT systems. As part of this research the latest technologies, systems and industry best practices were analysed, with a view to implementation on the Luas system to aid in the reduction of energy consumption.

2.1.2 Electric Railway Design

Electricity has become the choice of energy for railways and light rail systems around the world. Benefits of electrically powered rail systems over those powered by diesel engines include safety, security of supply and costs. Electric railway systems use fixed infrastructure installations in contact wires or running rails to supply a desired rate of electricity for use by the train or tram vehicles on the system. Light rail systems use both Alternating Current (AC) and Direct Current (DC) electrical supplies, depending on their design and location. In either case, the power supplied to the contact line or running rail is supplied by the system sub-stations. Sub-stations allow rail systems to safely regulate the power supply, separating the system from the main grid, creating their own mini grid system. Kiessling et al. [30], describe traction power systems from a planning, design, implementation and maintenance point of view. The characteristics of Luas power supply are similar to those seen throughout the French light rail networks. The French were the pioneers of modern light rail systems in Europe. Luas operates by way of an overhead catenary system (OCS) of 750 V DC with a stagger of 200 mm and a pantograph width of between 1600 mm to 1950 mm, power is supplied by the system sub-stations. Luas sub-stations have an incoming grid supply of three phase AC 10.5 kVA power. This AC power is then converted through oil filled rectifiers from its 3-phase AC to a nominal rate of 750 V DC. Original Luas sub-stations have a power rating of 1 MW, the sub-stations located on the extensions of the Luas system known as A1, B1 and C1 are rated 1.6 MW which offers greater power opportunities and capabilities [31]. A fit for purpose electrical system is paramount to a successful electric rail system. The reliability and uninterrupted supply of power is essential. Considerations must be taken into account when designing electrical rail infrastructure. These considerations should include vehicle technical specification such as motors, auxiliary loads, and weight. Operational considerations such as timetables, headways, average in-service operational speed, and the number of trams in-service. External factors such as routes, segregated and non-segregated track type, traffic signals, vehicular traffic and pedestrian traffic must all be considered. These variable factors will have an effect on the power system and provisions must be made in the design stage to cover all parameters and produce a system capable of supplying the desired power, even under the toughest conditions. Electric traction power systems will come under severe stresses and loads during the operational lifetime. Standards such as Railway Applications, Fixed Installations Electric Traction Overhead Current Lines 2001 (EN 50119) [32] and Railway Applications, Fixed Installations Protective Provisions against the Effects of Stray Currents caused by DC Traction Systems 2011 (EN 50122) [33], ensure electric traction power systems will remain reliable over their design life.

Cotton [34] discusses the return current circuit for DC light rail traction systems and outlines that current must pass back to the source of supply in order to complete the circuit. Running rails provide a return path for current and act as current collectors. As the running rails will have a longitudinal resistance, that will increase the further the tram vehicles are from the sub-station, inevitably a percentage of the return current will escape to earth which may have a lower resistance value. This current that escapes from the running rail to earth is known as stray current. Stray current can be potentially harmful to nearby underlying infrastructure. Any stray current that does leak from the system also makes the system less efficient, where current has to work harder to complete the circuit and thus increasing the overall energy consumption. To combat this stray current a number of systems can be put in place during the construction stage. Luas uses a stray current collector system. Effectively this is a matt of metal conductor bars installed under the track bed. The current collector system is electrically connected the entire length of the system and is subsequently connected back to each sub-station earthing system. The current collector system is used to conduct any stray current that has escaped from the running rails and divert it back to the sub-station. Stray current protection ensures the safety of neighbouring infrastructure, and increases the efficiency of the electrical system.

Correct sub-station configuration is essential for the optimal operation of a light rail system. Maximum import capacity (MIC) levels must be set before grid connections take place, and will determine the maximum capacity the network generator commits to supplying. Maximum import capacity levels determine the maximum electrical load available during normal operation. Once the MIC is set, the electricity provider will set the connection rates and standing charges based on its level [35]. To ensure correct rates are applied, optimal MIC levels must be set. An optimal MIC will ensure that during normal operation there is no breach of MIC. On-going monitoring of sub-station energy demand and energy consumption will ensure optimal sub-station settings are achieved.

2.1.3 Sustainability for LRT within the European Union

Light Rail Transit systems are now once again leading the way in efficient urban transport. Being electrically powered, emissions from LRT systems are generally low compared to other modes of transport. Light rail systems can however become more efficient in line with emerging modern technologies. The Luas LRT system is no exception, although a relatively new system compared to others seen throughout mainland Europe, Luas infrastructure and rolling stock were designed over a decade ago and many of the systems are now outdated. The EU was specifically consulted during this research for two main reasons. The first is that all EU directives in relation to energy efficiency and emissions such as the Energy Roadmap 2050 [14] are applicable to Ireland and must be implemented. The second reason is that the majority of European light rail systems operate to the same gauge and electrical design as Luas and as such are comparable for this research. There are also over 1000 Citadis trams operating throughout the EU including Dublin [36].

The Community of European Railway and Infrastructure Companies (CER) is a group of 77 railway and infrastructure members, including Iarnrod Eireann and Transdev. The CER’s main focus is to promote a strong rail industry, which is essential for the creation of sustainable efficient transport systems. This is achieved by lobbying at the political decision making stage of the European Union. The CER’s [37] describes sustainability in the rail sector, including improving overall efficiency by the integration of transport modes. Fuel consumption in private cars has decreased by 13% since 1995, whereas in the same period rail transport energy consumption has decreased by 21%, demonstrating the continuous endeavour to reduce energy in the sector. Carbon dioxide (CO_2) emissions for road transport stand at eight times that of rail transport. An earlier White paper by the CER [38], describes the strategy for sustainability and competitiveness in the European rail sector. This report is unique in that it not only looks at the energy usage within the sector, but also discusses the sources of power and security of energy sources into the future. This report raises questions regarding the use of an open grid electrical system for Europe. This would improve competitiveness and eliminate the huge monopolies seen in some EU countries. This open grid system would also make it easier for companies to sell electricity back to the national grid. Large rail operators may begin to generate their own renewable energy into the future with any excess power being sold back to the grid, providing a fresh revenue source. The European Rail Research Advisory Council (ERRAC) was set up in 2001 to represent and revitalise the European rail sector. The council consists of 45 representatives including operators, manufacturers and infrastructure managers. The council has produced many reports on the state of rail within Europe as well as strategies for future rail development. The ERRAC [39] reviewes the current status of Light Rail and Metro in Europe and discusses the rolling stock in operation and in production for future lines. This report highlights the need for increased LRT systems as a sustainable mode of transport for Europe. Recommendations were made to increase LRT systems around Europe, for their energy efficiency and their low environmental impact.

A substantial report produced by the European Rail Infrastructure Managers (EIM) [40] described a number of key issues regarding sustainability, carbon footprint, energy efficiency and biodiversity. Each area was examined by analysing the work that individual train operators had completed to date. Within the EU, in 2008, only 2% of the total transport sectors emissions were attributed to the rail industry [41]. This report examines the work the Norwegian National Rail Administration has undertaken into energy losses due to conversion from AC to DC, which is an issue all electrical powered rail systems experience. On average 20% of energy is lost during conversion from AC to DC, and this figure represents 75% of all energy losses around the system. The Belgian rail operator Infrabel [42] in partnership with Electrabel began the installation of 25 wind turbines during 2014 in what will be the largest land-based wind farm in Belgium. Once completed green energy generated from the turbines will be fed directly into the railway traction system to power high speed trains operating between Leuven and Liège. Infrabel [43] have also saved some 800 tonnes of CO_2 per year through the installation of 50,000 meters squared of solar panels on the roof of its high speed rail tunnel on the outskirts of Antwerp. The Community of European Railways [44] is a parliament lobby paper dealing with the growing rise in emissions from the transport sector in Europe. While total emissions within the EU have risen by 6% since 1990, emissions from the transport sector have risen 39%. This increase is due to the immense increase in passenger cars, heavy goods vehicles and air traffic. In order to achieve a reduction in emissions the EU transport sector has recognised that a modal shift to rail transport where a mix of fuel sources and significantly less emissions is desirable.

Railways are increasingly changing their power source to electricity, which significantly reduces emissions and utilises renewable energy sources. The European Union has set stringent targets for member states in relation to Greenhouse gas emissions, energy consumption and sustainability. The Energy Roadmap [14] is an EU directive which deals with the reduction in emissions, reliance on imported fossil fuels and renewable electrical generation. Key goals outlined in the report include reducing Greenhouse gas emissions to between 80% or 95% of the levels recorded in 1990, by the year 2050. The directive also recommends an increase in renewable energy sources to 75% of total demand by 2050. The directive states the need for efficient vehicles across all transport modes, and the need for behavioural changes among member state populations. The Department of Communications, Marine and Natural Resources [45] published a report detailing Irelands plan to deliver a sustainable energy future and details the projected primary fuel mix for electrical generation up to 2020 as shown in Figure 1.

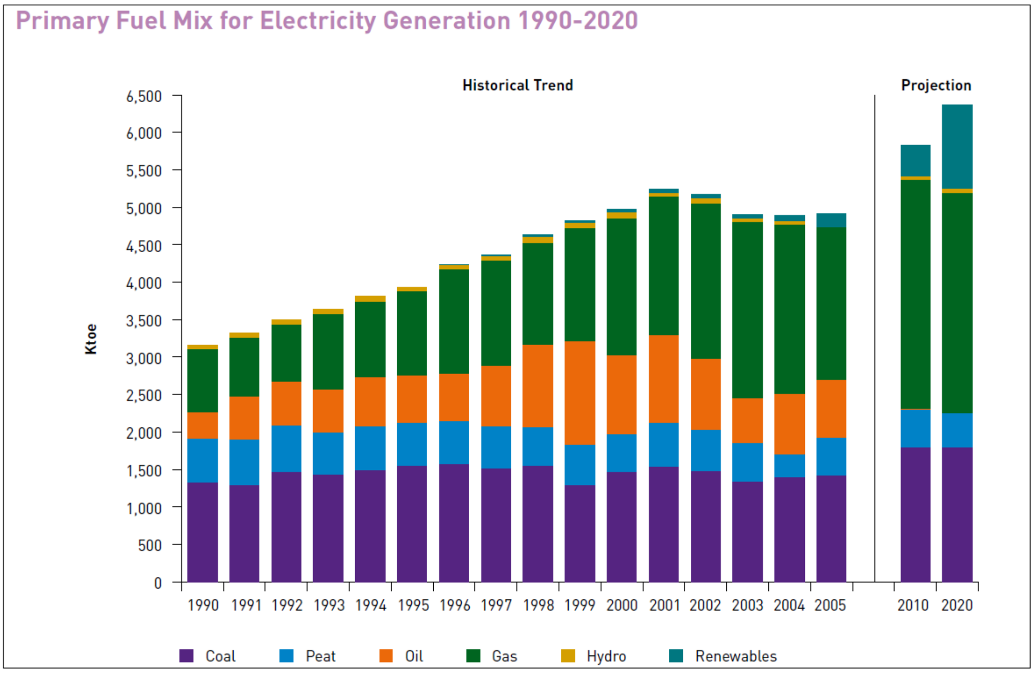


Figure 1: Irelands Projected Primary Fuel Mix for Electricity Generation [45]

The report discusses strategies to be taken to promote sustainable energy use within the Irish transport sector. The report also highlights the need for increased investment into transport related infrastructure to secure a sustainable future for the Irish transport sector.

2.1.4 Energy Storage Systems

Energy consumption in the rail industry can be reduced in a number of ways. One such emerging energy saving technology is that of energy storage systems (ESS). Light rail vehicles such as Luas use regenerative braking systems. When light rail vehicles are in traction, power is drawn from the OCS through the pantograph to the traction motors. When the vehicle is in braking mode, the traction motors reverse and generate power while simultaneously reducing the speed of the vehicle. The energy generated during regenerative braking can be utilized in one or a number of ways. The energy generated by the traction motors when in braking mode can be used to supply on-board systems on the tram that is braking. Power is distributed through the static converted to supply systems such as the passenger heating and ventilation system or the driver's cab air conditioning unit. If the current generated is too great to be completely utilized by the on-board tram systems then the energy which is generated under braking is supplied back through the pantograph to the OCS. This scenario can only occur if the OCS is receptive. In the case of the Luas system the OCS is receptive when it is less than its maximum voltage of 900 V DC and can accommodate the extra supply. This situation generally occurs when another tram vehicle is in the same electrical section as the braking tram and is drawing current from the OCS in traction. If the power is supplied back to the OCS it can be utilized by another tram drawing power. Should the current generated from braking be too great to be utilized by the on-board tram systems, and the OCS is not receptive as a result of its voltage being at a maximum, the energy generated from braking will be dissipated as heat through three rheostat resistor banks located on the roof of each light rail vehicle. When this scenario transpires a significant amount of energy may potentially be lost from the system. For instance at off peak times when the headways between trams are great enough, that no two vehicles are in the same electrical sections simultaneously to capitalise on this potential energy being generated.

Barrero et al. [46] suggest that as much as 40% of the energy supplied to operate a light rail vehicle could be recovered by regenerative braking and ESS. A number of ESS solutions have been developed to harvest the energy generated from braking. A second function of ESS is peak power demand shaving, where the regenerated power is used by trams in traction, thus reducing the draw from the electrical sub-station, especially during peak operational periods. Light rail operators must pay an above average unit price for electricity because of their high electrical demands during peak time periods. Energy storage systems technologies include include batteries, super-capacitors/ultra-capacitors and flywheels. Super-capacitors work on the same principals as batteries, however the new technology allows for a much faster charge and release of energy. Super-capacitors can also charge and discharge continuously without significant deterioration due to their construction. The construction of a super-capacitor includes two solid electrode current collectors separated by an ion permeable separator housed in a liquid electrolyte. This separator isolates the electrodes but allows ions of electrolyte to pass through. Charge is stored in the interface of the electrode and the liquid electrolyte, and is proportional to its area as shown in Figure 2. Because the charge characteristics are proportional to the surface area, super-capacitors have the ability to hold a large charge and release it in an instance [47].

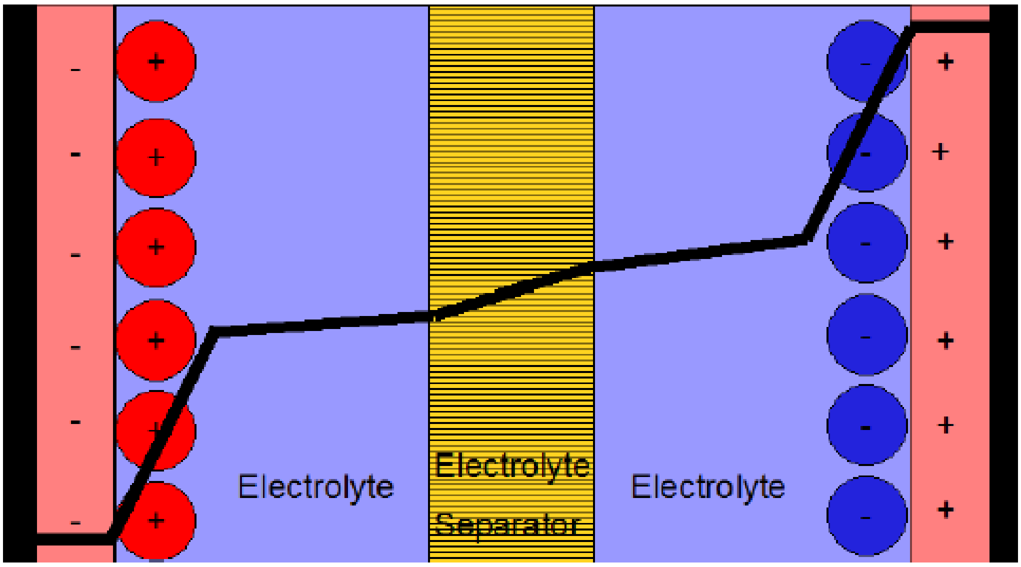


Figure 2: Construction of a Super-Capacitor [47]

As super-capacitors can operate in wide ranging climatic and altitude conditions and they have a much greater life cycle than conventional batteries. At present the technology is expensive, however on going testing and mass production will result in greater savings being achieved from using super-capacitor technology. Results from a case study based on the Brussels metro network [48], include energy savings of between 24% and 27% of total energy from the system sub-stations. As a result of adopting super-capacitors energy can be simultaneously saved and the network voltage stabilized. With the installation of a power flow control system, the power split between the grid and ESS is managed according to a set of parameters, determined by vehicle characteristics and operational conditions. Results show the acceptable life of the ESS to be 1,000,000 charge and discharge cycles. Results will depend on many factors, the best results were observed using the biggest ESS (1.56 kWh) on the heaviest tram 6 ppm^2, where energy savings of 26% of total power were recorded.

Jisheng Hu [49] discusses the design of ultra-capacitors. The system in question uses a bidirectional converter, linking the traction inverter DC link and the ultra-capacitor. This allows the system to store the regenerative energy when in braking mode and reuse the power in traction. As the characteristics of light rail systems are frequent stop start motions, most of the energy used in traction is to overcome the vehicles rolling resistance and potential energy. Once in traction, light rail vehicles are extremely efficient due to their wheel-rail interface which contains little friction. When in braking mode, high levels of current are generated and stored in the ultra-capacitor. As most LRT systems in urban areas operate a DC system with voltage varying from 600 to 900 V DC for public safety reasons, there are limitations on the voltage capacity of the line. In theory if all the light rail vehicles on the line applied the brakes at the same time the power generated would cause an over voltage on the line. Such a scenario would see the excess energy being dissipated as heat through the rheostat resistors on each tram. In the opposite instance during off peak operating hours the headway between trams may be too great to realise regenerative braking, where the instantaneous energy generated will be dissipated as heat in the rheostat resistor. Therefore the utilisation of regenerative braking during off peak operations is lost. In ultra-capacitor design the electrical charge and discharge credentials are efficient in storing power and in effect reduce the energy consumption of the tram. One major advantage is that ultra-capacitors can easily be retro-fitted to any light rail vehicle. No changes to the original design needs to be made, only a simple modification to allow connection in parallel between the traction motor circuit and the ultra-capacitor using a bidirectional DC to DC converter. This allows the energy generated to be sent back to the OCS when the potential of the OCS can accept it, or store the energy in the ESS when the OCS is non-receptive. In conclusion the report suggests that this ultra-capacitor design can increase the realisation of the regenerative brakes from 20% to 80% - 100%. A paper from the Ticket to Kyoto [50] reviews the energy storage technologies being applied in the public transport field. The report finds that many pilot projects have been conducted throughout the world. However, full scale applications are slow to be implemented. Each solution has both advantages and disadvantages to each light rail operation. Ticket to Kyoto is assisting five research partners with the evaluation and implementation of energy storage systems for light rail vehicles. Mir et al. [51] validated the feasibility of super-capacitors by means of laboratory and full scale line tests. The design and use of super-capacitors to replace the overhead catenary system in certain parts of the line was examined. Overhead catenary systems are seen to have negative visual impacts to urban areas, and can be deemed intrusive to local historic architecture. One solution is to operate certain sections of track without OCS, however the power supply must come from somewhere. Super-capacitor power supply was tested using 500 meters of OCS free track. The important characteristics that were considered included the power requirements, capacity and volume of the super-capacitor, weight, efficiency, and life expectancy. Testing criteria included an average speed of 15 km/h for the 500 meters of track section and a gradient of no greater than 0.6%. Prior to the test a full charge of the super-capacitor was completed. On completion of both laboratory and field testing, Mir et al [51] validates the use of super-capacitors for this 500 meter OCS free section of track.

Another type of energy storage systems investigated was wayside (trackside) energy storage systems (WESS). These systems can be used as an additional power source for LRT systems or in some cases can act as a replacement to conventional sub-stations. Wayside energy storage systems work on the same basic principles of a conventional sub-station, supplying power to light rail vehicles through the OCS. However these systems do not have an incoming power supply from the grid. Instead WESS harvest the excess energy accumulated on the OCS from regenerative braking. Like a traditional sub-station, this excess energy acts as the incoming power source as shown in Figure 3. The energy is stored in an energy storage medium and released when a tram, in the same electrical section draws power in traction. This storage medium can be in the form of a number of technologies such as super-capacitors or flywheel storage systems.

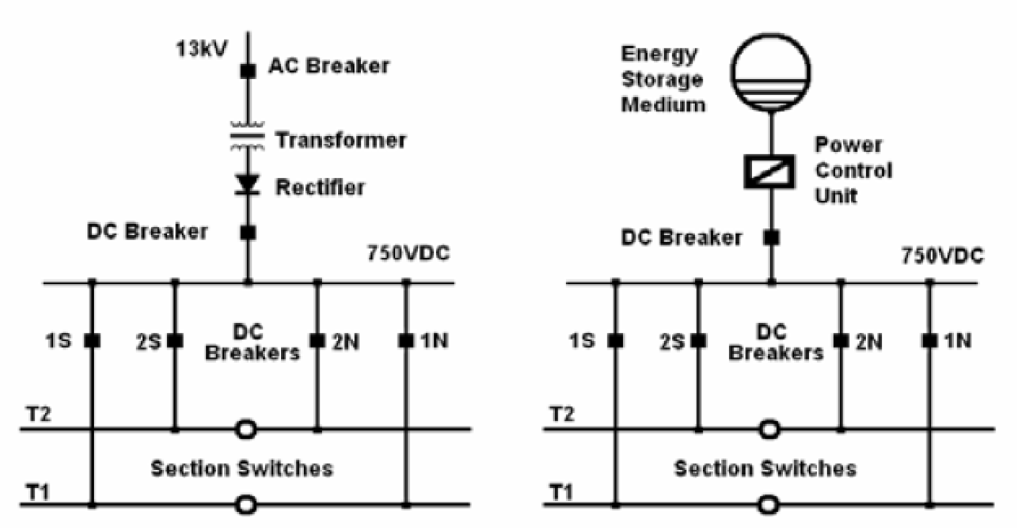


Figure 3: Wayside Energy Storage Systems Configuration [52]

J.G Yu [52] produced test results from a simulation test for a WESS system. This specific WESS simulation test was conducted with particular set parameters that reflect the standard LRT systems seen in operation in Europe, including Luas. The report concluded that a full integrated WESS replacing an existing standard sub-station would save $45,000 (€33,000) per year (based on published US electricity prices). Other factors such as timetable or service changes would also have to be taken into account when considering such solutions. This estimation must also be evaluated against local electrical unit costs, capital investment and LRT operations, but it is a good indicator that WESS may be a viable solution to reducing energy consumption and reducing the amount of traditional sub-stations required when constructing an LRT system. Advantages of WESS include no major modification to existing infrastructure and no safety related concerns when compared with on-board energy storage systems. Disadvantages of such systems include the indebt research which must be compiled to determine the optimal location for the WESS. With these systems there is no possibility of OCS free operation, and the system remains limited to the tram vehicles operating in the same electrical section. Based on this research it has been determined that energy storage systems are best served by the use of super-capacitors. As a result specific costing's and simulations for the use of ESS for Luas was carried out, based on the use of super-capacitors.

2.1.5 Lighting Systems

Traditional lighting technologies such as Compact Florescent Lamps (CFL), Metal Halide, Mercury Vapour, or Sodium lamps have become outdated and inefficient compared with modern lighting technologies [53]. Lamp technologies have advanced significantly in recent years. With these advances, the upgrading and retrofitting of aged light fittings is an attractive investment for industries. Options available include Light Emitting Diode (LED), and Magnet Induction Lighting (MIL), both offer lighting solutions at a fraction of the energy consumption compared with traditional lamps. These fittings also offer a better lighting quality and lower maintenance costs. Wan Norsyafizan [54] offers design theories for efficient building lighting systems. Typically lighting can consume anywhere from 20% to 50% of a buildings total energy consumption. These high percentages come as a result of improper lighting designs. Many older buildings may also be unnecessarily over illuminated in some areas and under illuminated in others. Modern lighting designs calculate the appropriate lux levels required in each area of the building and design accordingly. Matlab simulations can now be used to determine efficient lighting designs. Inputs to the calculation include characteristics such as floor area, required lux and initial lamp lumen. The aim is to determine the minimum wattage lamp which will satisfy the lux level and lighting quality needs, and to install fittings in an intelligent fit for purpose approach. With MIL's achieving a 50% reduction in energy consumption, and appearing to have a brighter, better quality light to the human eye they are increasingly being used to replace older fittings. In MIL fittings, electrical ballast sends high frequency energy through wires to the inner induction coil which is housed in a glass tube. This creates a magnetic field which excites mercury atoms, and in turn creates an ultraviolet light (UV). This UV light is converted into visible light by phosphor coating inside the tube. Energy savings are achieved as the ballast can run at efficiencies of between 95% and 98%. Maintenance savings are also achieved with MIL's, as their lifespan is typically between 80,000 and 100,000 hours, compared with between 18,000 and 22,000 for Sodium or Metal Halide. Magnetic Induction lights also operate at 100% light output for their entire lifespan whereas Sodium or Metal Halide lighting levels can deteriorate by as much as 40% nearing the end of their lifespan. Magnetic Induction Lights were investigated as a possible replacement for fittings around Luas infrastructure including stations, depots and car parks.

Guan et al. [55] simulates luminous levels of tube like LED lights to replace conventional fluorescent tubes. Light emitting diodes emit light by the movement of electrons in a semiconductor. Energy is released through electron holes in the device, in the form of photons. The colour of the light within the diode will be relative to the size of the semiconductor. Because there is no filament the lifetime of LED fittings is greatly increased in some cases by 50,000 hours. Light emitting diodes also offer new lighting effects at a fraction of the energy usage. The research models a specific LED tube of 580 X 25 X 1 mm to replace traditional fluorescent tubes as shown in Figure 4.

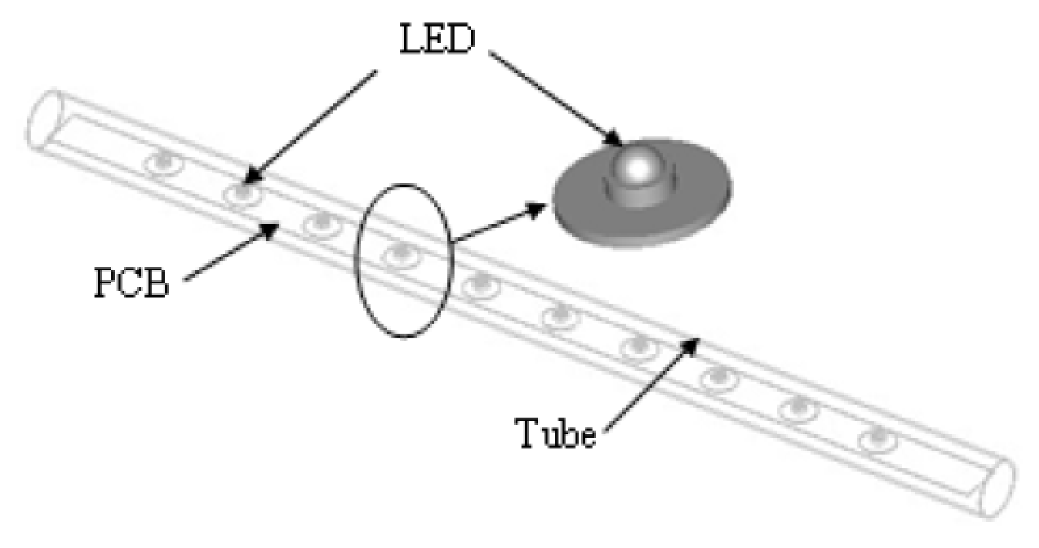


Figure 4: LED Tube Construction [55]

This is of interest to this research as Luas trams currently use this type of fluorescent tube in the passenger saloon area of the tram vehicles. Results of the simulations show that the LED fitting tested and modelled can achieved the desired luminous levels of approximately 50 Lux, matching the traditional fluorescent tube fitting but at a fraction of the power use. No major modifications have to be made to install such fittings. In the case of Luas trams, the ballast powering the original fluorescent tube may be bypassed, with the LED fittings being hard wired. Significant savings have been simulated by using similar type fittings.

2.1.6 Heating and Ventilation Systems

Passenger satisfaction has become an increasingly important factor for transport operators. According to the European Commission's report on passenger satisfaction with rail services [56], "*59% of people are satisfied with rail frequency and 57% are satisfied with the maintenance and cleanliness of trains and stations".* Another element of passenger satisfaction is passenger comfort. Comfort can be quantified in a number of ways including noise, ride comfort and air quality inside the transport mode. Heating, ventilation and air conditioning (HVAC) units have become standard on all modes of public transport. Light rail systems are arguable one of the most difficult modes of transport to control the quality of air within the vehicle. Because of their nature of short journeys and a frequent number of stops the passenger saloon air is constantly being recycled when the doors are opened at stations. Luas has the added pressure of operating in a maritime climate, where the average temperature is low and there are excessive amounts of wind and rain. Luas is also unique in that it only has a heating and ventilation system installed on its tram vehicles, as there is no requirement for an air conditioning module, due to the low operating temperatures. The desired temperature setting range for light rail vehicles is generally between 12°C and 18°C, and will be determined by factors such as external temperature, internal temperature and CO_2 levels within the saloon. In Dublin the majority of the time the temperature of the external air will be lower than the desired air temperature inside the vehicle. As a result the heating and ventilation system, is working strenuously to maintain the desired internal temperature. This will inevitable increase the energy consumption associated with the systems. Luas vehicles were designed over a decade ago and the heating and ventilation systems installed are now out-dated and less efficient than the present day alternatives.

Neu [57] used a building software system known as EnergyPlus [58] to calculate the most efficient air condition and heating setting for Luas vehicles. The system was originally designed for use on fixed building structures and not moving vehicles. However the system had been manipulated to produce results for a moving light rail vehicle. Factors such as direction of travel, altitude, and climate are all considered. Vehicle specific data such as thermal efficiency, U and R insulation values were combined and entered into the software system. The system produces results on desired air temperature, air quality and carbon dioxide levels. With the optimal parameters identified, solutions to acquiring the results were examined. Three solutions were identified including, optimisation of the ventilation, increasing the thermal insulation of the vehicle, and replacing the resistor heaters with radiant heating mats. These solutions have been estimated to achieve a 60% energy saving of the heating and ventilation systems on Luas vehicles. Haller [59] describes the characteristics of thermal comfort for passengers in rail vehicles as *"Thermal comfort is described as a perception by passengers that the surrounding air is of an ideal temperature, quality and humidity, where passengers would not prefer a warmer or cooler level"*. Thermal comfort is influenced by personal factors such as activity, clothing and journey time. Spatial factors include radiant temperature, surface temperatures and ventilation factors such as air speed, air temperature and relative humidity were all considered. These factors must be taken into account when investigating modifications to Luas heating and ventilation systems. Safety parameters such as carbon dioxide levels and humidity levels were also considered. Any energy saving modifications to Luas heating and ventilation system would have to maintain these air quality standards and comply with EN 14750-1 of 2006.

Richter [60] discusses the cost of HVAC units operating throughout Europe. Tests were performed using a tram vehicle in a specially designed wind tunnel. Simulating track and climate conditions extensive testing was carried out. The energy consumption of the HVAC system was specifically recorded separate to the other auxiliary systems on the tram. Both the cooling and heating elements of each of the three HVAC systems were recorded using power measurement meters. The tram vehicle in this test was designed, allowing for between 15% and 22% of total power drawn from the OCS for use on the HVAC system. After testing it was found that the HVAC unit was consuming as much as 34% of total traction power. This is an excessive percentage of total power to be consumed by the HVAC system in a simulated month of July. Testing results highlighted that modern tram vehicles use significant amounts of power to maintain thermal comfort levels. As most of these systems were designed not to work in conjunction with tram location and door opening times, there is a potential to save significant amounts of energy through modifications to existing HVAC units. A test of Luas heating and ventilation system during this research recorded consumption figures of between 20% and 60% of total tram power. Because of Ireland's ever changing weather conditions these percentages can vary significantly. Heating and ventilation systems can be designed more intelligently, linking the ventilation fans to door openings, reducing the desired set point in warmer months and disabling the system when not required.

2.1.7 Rolling Stock Bogies and Traction Motors

Major advances have been made in both axle and traction motor technologies over the past decade. New materials and intelligent designs have significantly reduced the weight and increased efficiency of these essential rail components. A number of companies are now producing light weight bogie designs for the rail industry. A reduction in bogie weigh will result in an energy saving through reduced efforts both in traction and braking. Maintenance savings can also be achieved as these new light weight bogie designs have less impact on infrastructure, reduce the displacement of ballast and result in a better wheel rail interface. Kawasaki [61] produced energy savings of 10% and reduced CO_2 emission of 16,000 tonnes per year in tests performed on the Taiwan high speed rail line. Reductions were as a result of reducing the weight of their high speed axle loads, from 17 tonnes to 14 tonnes. Weigh savings were achieved as a result of a new bolster-less bogie designs. International manufacturers such as Bombardier and Alstom are producing light weigh bogie designs for light rail vehicles. These include the use of tougher, light weigh components in construction. These bogies include bolster-less designs and are 100% low floor for ease of access to tram vehicles. The Bombardier [62] bogie comprises of a bolster-less design with standard axle technology as shown in Figure 5.


FLEXX Urban 1000
FLEXX Urban 2000
FLEXX Urban 2500

Figure 5: Bombardier Flexx Urban, Light Rail Bogie Options [62]

The short wheelbase allows for smooth running in tight urban surroundings and is capable of speed up to 70 km/h. Alstom [63] provide a choice of three bogies for their Citadis tram fleet, all of which are 100% low floor and are capable of speeds between 70 and 100 km/h. Traction motors for use in the rail industry have also advanced significantly in recent years. Smaller structures, efficient drives and advanced gearings have all combined to reduce the power requirements of traction motors. Luas vehicles uses synchronised AC traction motors to power the motors bogies of the vehicle. In this type of system a rotor spins (within a stator) with coils passing magnets at the same rate as the alternating current producing a magnetic field.

Synchronised motors have zero slip under normal operation, when the slip value is positive the motor is using power to turn the reduction gears. With most light rail vehicles these traction motors have the ability to produce energy under braking. In this instance the motor reverses, the slip is negative and the motor is generating power. The multinational corporation, ASEA Brown Boveri (ABB) [64] are producing modern efficient traction motors for rail and light rail vehicles. These new motors have a compact light weigh design. Innovative cooling arrangements and extended operational life times. These new designs offer maximum torque with minimum weigh which results in maximum efficiency. Motors can now also be designed specifically for a vehicles operation. Factors such as operation cycle, available space, environmental conditions, grid voltage variations, wheel diameter differences, and traction converter characteristics can now all be implemented in the design stage. The result will be a fit for purpose motor that will be durable and efficient. ABB also offer the choice of gearless direct couple motors. These may be an option on future rolling stock, however incorporation to existing bogie designs would require major modifications to tram vehicles, updating of original engineering manuals and annual maintenance plans.

2.1.8 Renewable Energy Generation

As fossil fuel stocks are increasingly in short supply, governments and industries alike may adopt renewable energy generation technologies. Renewable energy solutions are becoming increasingly visible in Europe, growth in the area has continued to increase. Strict targets have been set by the European Union to achieve 75% of total energy demand, generated by renewable sources by 2050 [14]. As a result individuals are now also being encouraged to contribute to renewable energy generation. Transport is one of the largest consumers of energy in Europe, as a result transport industries should be one of the first to adopt these new practices. The Railway Technology Journal [65] describes the Tenerife light rail system as having an ambitious plan to generate 100% of its power needs through renewable sources by 2020. The system which opened for operation in June 2007 is planning to build ten wind turbines, which will have the capability to produce 10 MW of power, more than enough to operate the 12.5 km of track and twenty Citadis 302 style trams. The wind turbines will be part of the LRT infrastructure and will be operated and maintained in-house by the Metropolitano de Tenerife. This will result in a 100% zero emissions, carbon neutral system, which if realised will set the standard for efficient sustainable light rail transport.

Chen [66] investigates the progression of renewable energy sources and the impact to countries national grid systems. Industries are turning to electricity as their source of energy. Some 60% of all energy consumed by industry is now sourced as electrical power. Electrical power production is changing from traditional natural fossil fuels such as oil and coal to renewable sources such as wind and photovoltaic cells (PV). As this change takes place, grid systems must also upgrade to accommodate these new sources of energy, allowing their penetration to national grid systems. One problem witnessed with renewable sources of power is their strong dependence on weather and the uncertainly of their output. This must be taken into consideration when thinking of upgrading to renewable sources such as wind or PV. In transport the security of power is essential to provide a continuous, reliable service. Any operation that is relying on a renewable source of power must ensure the source is capable of providing continuous power in excess of what is required. If this cannot be guaranteed a backup source of power such as a main grid connection must be maintained. This research focuses on both wind and PV as renewable sources of energy. Costs for both generation types are decreasing year on year thanks to improved technology and mass production. Certain factors must be taken into account when considering renewable energy sources, including reliability, efficiency and cost. Variable speed wind turbines are the preferred choice by most EU countries. These allow for easier grid connections using power inverters giving maximum controllability. Grid connections vary from country to country, it is essential to ensure compatibility with your local grid before installing renewable energy generation technologies. Requirements for wind turbine generators connecting with the national grid in Ireland are set out in the EirGrid grid code. In order to meet these conditions it is imperative to have full control over your source. In conclusion, renewable sources of energy may be considered by countries, industries and individuals to aid in increased sustainability. Before the installation of renewable energy sources, considerations such as surrounding grid and inter connection infrastructure should be considered. New technologies of power applications, flexible grid structures and micro grids can aid in the harmonization of renewable sources of electrical generation.

2.1.9 Human Factors and Efficient Driving Styles

Efficient driving styles within the rail industry as a whole have been researched and analysed in great detail in order to improve efficiencies in energy consumption and reduce rolling stock maintenance. The Ticket to Kyoto [67] case study of the Brussels Metro eco-driving programme highlighted that a reduction of 12% of total traction power was possible after a relatively inexpensive measurement system was installed and one hours training per driver was provided.

The initiative resulted in an 11,500,000 kWh saving in its first full year. It is imperative that the utilisation of optimal driving styles must only be enacted once the relevant human factors have been taken into account. Human factors deal with the relationship between the human, equipment and devices used in the course of work. Although human factors in the rail industry have been significantly researched over the past twenty years by operators such as Deutsche Bahn's and Network Rail, it is still the opinion of many experts in the field that large gaps exist in the understanding of the effects of human factors on the safe operation of rail networks. When compared to the airline industry, the rail industry lacks in developing technical solutions to mitigate against the risk of human factors. The fundamental aim of any rail operator is the safe movement of people. Train and tram drivers are one of, if not the most safety responsible persons in rail operations [68]. In the initial training of train or tram drivers the main focus is always on safety. To change the training dynamic to incorporate optimal driving efficiencies to help reduce energy, a risk assessment incorporating the relevant human factors must be considered. The introduction of such training to drive in an optimal, efficient style requires an increased technical knowledge of the train or tram systems by all drivers. Inevitably the work load for drivers will be increased, with the potential human error also increased [69].

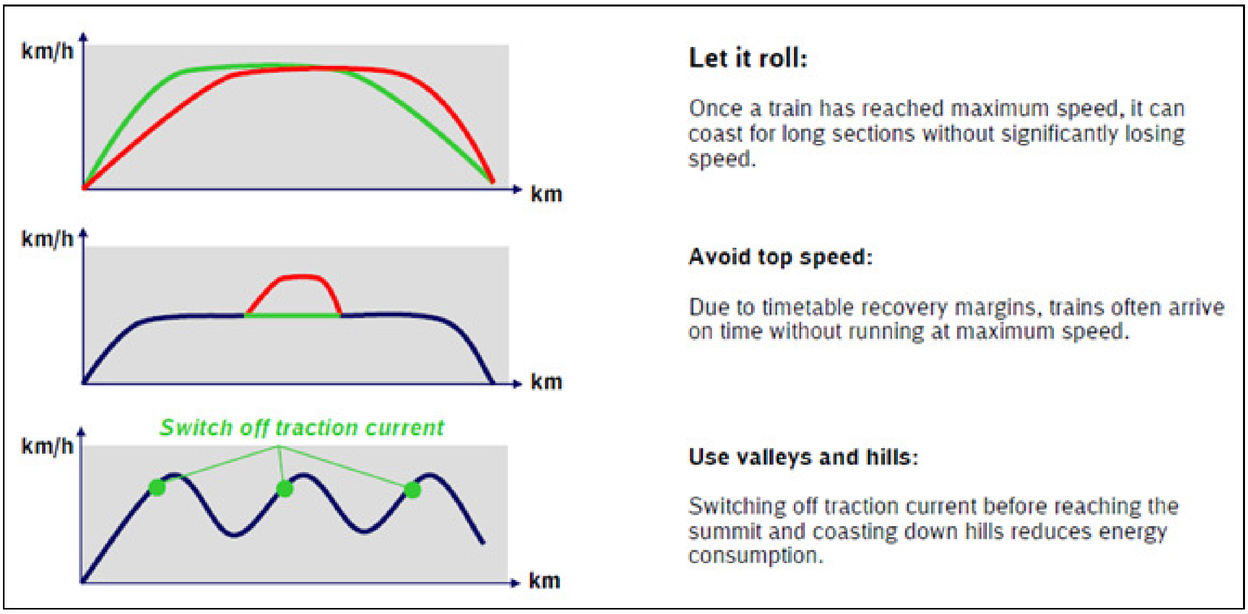
Hartley [70] analyses the Human Factors attributed to the change of rail vehicles specifically the drivers cab. Rolling stock generally has a life expectancy of 35 years, over this time components and systems become obsolete and require modification or replacement. The systems most often added or changed in rolling stock cabs are driver advisory systems and comfort systems. Any new or modified system would have some form of interface with the vehicle driver and may have the potential to impact safety. The research discusses the installation of a driver advisory system for efficient driving as a means to reduce energy. To ensure the effective integration of new technologies a human factors checklist should be completed. The checklist asks such questions as;

i) Are additional tasks being introduced?

ii) Are their conflicts with existing tasks?

Appropriate risk assessments need to be conducted when modifying a rail vehicles cab. Ultimately any new technology requiring human interaction should be introduced with the appropriate human factors analysis.

Energy consumption differences can be significant between different drivers and driving styles. Research has found differences in the total energy consumption of up to 40% for tram operations on the same routes at the same times. In Germany, Deutsche Bahn (DB) implemented a significant change management programme relating to energy efficient driving across its entire network in 2009 [71]. The programme included the training of the then 12,000 drivers. This included the theoretical training on the efficient use of the train systems. Training simulations in a specially designed full size simulator and coaching trips on trains operating on the main line to practice efficient driving techniques. In order to evaluate the programme and analyse results, 3,500 traction units across the DB fleet were equipped with energy meters to analyse consumption trends. The main energy saving techniques identified as part of the analysis included “let it roll”, avoid top speeds and use hills and valleys. “Let it roll” is a technique where once the train has reached its desired speed it can coast for long periods without losing significant speed. Avoiding top speed is another technique which was utilised to reduce energy consumption, utilising timetable recovery margins ensuring trains do not arrive late. The third technique which had a positive impact on energy consumption was the use of hills and valleys. Drivers were trained to switch off the traction units before the summit of a significant hill and allow the train to coast down the inclination.



Let it roll:

Once a train has reached maximum speed, it can coast for long sections without significantly losing speed.

Avoid top speed:

Due to timetable recovery margins, trains often arrive on time without running at maximum speed.

Use valleys and hills:

Switching off traction current before reaching the summit and coasting down hills reduces energy consumption.

Figure 6: Deutsche Bahn Driver Training Techniques [71]

The aim of the programme was to achieve significant reductions in energy and sustain these reductions across its entire network. Continuous training was provided, drivers received on-going reviews and incentives were provided for compliant drivers. The DB enacted an energy saving competition for drivers, this resulted in an appetite for success. The results of the initiative entitled *"Energy Efficient Driving"* included an overall reduction in energy consumption of 5% for the period 2002 through to 2006 on the main line operating the DB Class 225 locomotives.

Intelligent Energy Europe [72] commissioned a report on energy efficiency good practices by the railways, where it aims to reduce the energy consumption in the five European countries with the largest rail networks. One of the main aspects of the report was energy efficient driving (EED). The report highlighted the inefficiencies associated with short term driving, where maximum acceleration, maximum speed and maximum braking techniques were general practice in order to ensure on time operations. Energy efficient driving can be implemented in one of three ways. The first is through extensive training and awareness of EED practices. The second is through the installation of special on-board equipment to guide drivers. The third is timetable reviews and changes. Analyses of timetables identify potential buffer periods where the timetable may be slightly altered. Generally timetables allow for between 5% and 12% recovery time against the minimum run time. Adjusting the timetable buffer, will allow for changes in driving practices with the aim of reducing energy consumption. By implementing the EED strategy, savings in energy consumption of 11% were recorded for a 3.9% increase in the timetable running time [73].

2.1.10 Comfort of Light Rail Transport

Light rail systems are favoured as a solution to urban transport needs as a result of accessibility, frequency and the lower cost of construction when compared to Metro systems for example. LRT systems are also deemed to be a more comfortable form of short and medium distance transport when compared to buses. The main factors which relate to the perception of quality and comfort include reliability, ride comfort, availability of seats, heating / air conditioning, space and cleanliness.

Litman [74] evaluates rail transit benefits, challenging the view that they are ineffective at reducing congestion and are financially wasteful. The research states *“if the transit service is comfortable where passengers have a seat and vehicles are clean, passengers will be able to relax and work”*. This more comfortable offering when compared to bus transport will increase the passenger share and as a result reduce the operating costs. Liman states for bus transport to match that of light rail in terms of quality and comfort the capital costs required to be invested would then equal or surpass that of LRT capital costs as a result of modifications to bus vehicles, bus stops and switching to alternative fuels.

Swanson et al [75] discusses the planning and design of the new LRT system for Phoenix, Arizona, in the United States of America. Following considerable public consultations great emphasis was put into improving various aspects of the light rail vehicles including comfort. This was achieved by using the latest technologies available at the time of design and construction. One of the major concerns in relation to passenger comfort was keeping the light rail vehicle cool when operating in external temperatures exceeding 37°C. To ensure a passenger compartment which was cool enough during these conditions two large HVAC units were fitted to the vehicles. Reflective window tints were fitted to the vehicles glazing and low heat emitting LED lights were also installed within the passenger saloon. Testing of the capabilities of the HVAC system was conducted inside a climatic chamber which could simulate external temperature in excess of the maximum temperatures in Phoenix. The interior was fabricated and painted in cool colours such as green, grey and light beige all of which added to the perception by passengers that the transport mode was inviting when compared with the extreme external temperatures. The interior has cushioned seats reinforced with Kevlar, there is good visibility including through the drivers cab with a glass partition. These design features are now standard on all modern light rail vehicles, including Luas the result of which is improved comfort for passengers and increased passenger satisfaction.

Fox [76] outlines the reasons why Portland in the United States of America chose a light rail system over buses as a solution to their urban transport needs. Street cars have operated in Portland since 1986 and due to the initial success of light rail it was the preferred option when the decision to expand the public transport network was taken. One of the principal reasons LRT emerged as the preferred option was as a result of the increased comfort afforded by a tramway. A survey conducted in Portland indicated 80% support for an expanded light rail network. It is thought that this high support is as a result of the smoother, faster and generally more comfortable offering of light rail when compared to bus transport.

At a conference entitled "*Tramway Club*" held in Barcelona, Spain on 26th March 2015, [77] representatives from 15 countries attended to discuss the future of LRT systems. One of the main themes throughout the two day conference was the comfort and passenger experience that LRT systems could offer. The future of LRT systems depends greatly on passenger numbers for a sustainable operation. In order to attract passengers, major emphasis must be placed on providing the best in class passenger experience by improving comfort and addressing security requirements. The Casablanca, Morocco [78] LRT system, L2 currently under construction has an objective to increase the public transport share by 8% by 2019. To achieve this, the strategic plan 2015-2020 [78] aims to provide a connected metropolis area through LRT. The system will be affordable, safe and a more comfortable choice when compared with private car transport which is the dominant transport mode presently.

2.1.11 Light Rail Best Practice

It is widely recognised that LRT systems are the most efficient modes of urban transport. Light rail operators strive to maintain this recognition of efficiency and sustainability by constantly seeking ways of reducing energy and emissions, and as a result increasing efficiency. The Barcelona LRT system, operated by Transdev [79], integrates over 250,000 square meters of grass track, improving noise levels and reducing emissions during construction. In Paris [80] an Alstom produced super-capacitor system known as STEEM is in operation. The system stores the energy generated in braking and supplies this power back to the vehicle when the traction mode is regained. The system also has the ability to charge the super-capacitor when stationary at stations. Results from testing show a 16% reduction in total traction energy consumption. Super-capacity technologies have also been tested as a substitute for OCS free running in sections of track which are of historic architecture. Alstom [81] are also testing a wayside energy storage system (WESS) known as HESOP in their manufacturing plant in La Rochelle, France. The system harvests the power generated during braking and stores it in a WESS using super-capacitor technology. This stored energy is then supplied back through the OCS to when a vehicle in the same electrical section draws traction. The stored energy reduces the consumption from the grid through traditional sub-stations. As a result the overall energy consumption of the system is reduced. Tests have recorded savings of 15% of total traction power. De lijn, [82] operators of the Flemish light rail system in Ghent Belgium have an innovative solution to reduce the energy consumption of their HVAC systems. Modifications were made to the HVAC unit by installing a motorised flap on the air inlet to reduce its surface area and reduce the amount of fresh air inhaled by the system. Sensors within the vehicle saloon continuously monitor levels of CO_2, temperature and humidity. A custom designed control system regulates the HVAC's operation, including the motorized flap on the air inlet as shown in Figure 7.

Figure 7: De lijn Modified Heating and Ventilation Unit [82]

The system is operated, to a safe minimum level of heating or cooling, while ensuring comfort. Savings have been achieved totalling 20% of total power with a return on investment of just over one year.

In the Netherlands [83], it is envisioned that by 2017 up to 95% off all energy required to operate the electric rail network will be supplied by wind turbines. The wind turbines are located offshore and once fully operational will be capable of supplying 1.4 TWh of energy. The project aims to reduce CO_2 emissions by some 2,400 tonnes per year. In Mannheim, the German operator, RNV [84] recorded traction power savings of 30% from the use of super-capacitors.

The system produced by Bombardier is known as MITRAC. These systems of super-capacitors have a charge capacity of 3 kWh, and have forecasted savings of 93,000 kWh per year across the system. A second type of energy storage system has been tested on the Piccadilly line of the London Underground rail network [85]. Here a static flywheel technology is used to store the power generated from braking. The flywheel is a rotating disk, spinning around a static axle. The energy is stored in a kinetic form. Results from testing on the Piccadilly line recorded savings of 28%, note the system was coupled with a power supply reinforcement system. From this literary review it is clear that the light rail industry throughout Europe is investing and pioneering innovative solutions to reducing their energy consumption. While not every solution will be appropriate for every operation, a mix of solutions can be adopted in a bid to reduce energy requirements.

2.2 Luas Light Rail Operations

At this stage in the thesis it is important to introduce the Luas LRT system. This section of the thesis describes the Luas contractual structure, the key stakeholders involved in the daily operation and maintenance of the network, the current routes and the passenger services operation.

The main sources of literature for this section were contractual documentation and performance reports provided by Transdev and Transport Infrastructure Ireland

2.2.1 Operational Structure

Transport Infrastructure Ireland formerly RPA are charged with the procurement of the light rail and metro projects in Ireland, including Luas. In the initial planning phase of Luas it was recommended, to achieve the best efficiencies that the Luas system should be operated by private industry. As a result four contracts were released for tender. They were The Luas Operating Contract, the Vehicle Maintenance Contract, the Infrastructure Maintenance Contract and the Ticket Vending Machine Supply and Maintenance Contract. Transdev currently hold the operating contract rights until September 2019. As part of the operating contract Transdev are tasked with the effective and efficient operation of the system, meeting specific requirements and performance targets set out in the operating contract. Transdev must also manage the maintenance contractors on a daily basis, ensuring compliance with their respective contracts allowing a seamless operation of the Luas system. Alstom Ireland holds both the Vehicle and Infrastructure Maintenance Contracts and the German company Scheidt and Bachmann hold the Ticket Vending Machine Maintenance Contract. Throughout all contracts both preventative and corrective maintenance is on-going twenty four hours a day across the system and at both Luas depots. There are in excess of 500 employees working for both the main contractors and sub-contractors across the Luas network. Figure 8 outlines the Luas organisational structure [86].

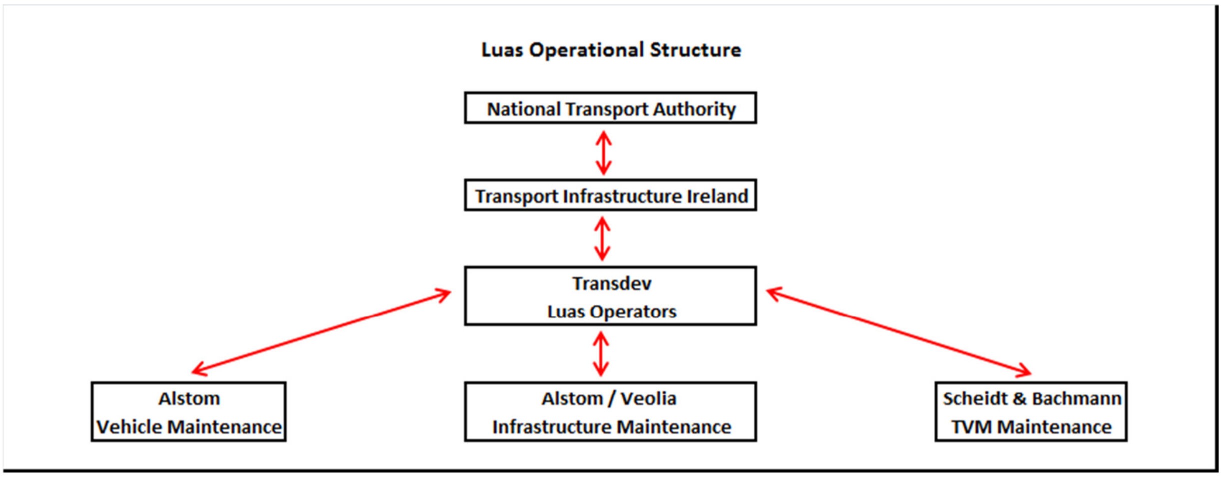


Figure 8: Luas Organisational Structure

2.2.2 Luas Routes

The Luas light rail system operates over two lines known as the Red and Green Line in Dublin city centre and surrounding suburbs. The Red Line began operating passenger service on the 29th of September 2004. Extended on two occasions, the Red Line now has a total of 19.5 km of track serving 32 individual stops. The Red Line currently operates two passenger service routes. The first from Saggart to Connolly is 17.4 km. The second from Tallaght to the Point is 16.2 km. Figure 9 details the stops located on the Red Line.

Figure 9: Luas Red Line Map [87]

The Red line infrastructure consists of both segregated (permanent way) and non-segregated (shared running) sections of track. Track bed type includes embedded, slab, grass, ballast and plinth. Located at 5 meters above sea level at its lowest point and 109 meters at its highest, the Red Line has a gradient profile of 104 meters as shown in Figure 10 [88].

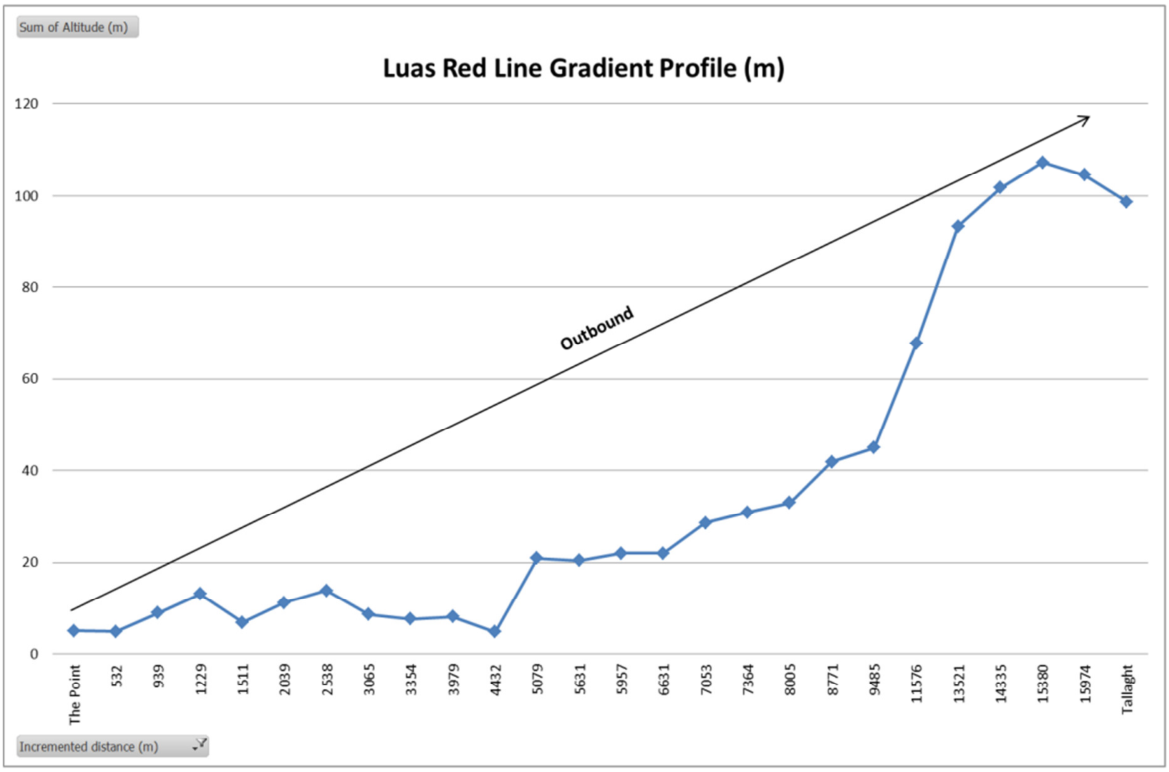


Figure 10: Luas Red Line Gradient Profile

The Luas Green line began operating passenger services on the 30th June 2004. Extended in 2010 the Green Line total track length is 17.5 km and serves 22 individual stops. The Green Line also operates two passenger services. The first from St Stephens Green to Sandyford is 8.8 km. The second from Brides Glen to St Stephens Green is 16.3 km [87]. Figure 11 details the 22 stops along the Green Line.

Figure 11: Luas Green Line Map [87]

The majority of the Green line is segregated track using the same route as the old Harcourt Railway line, where a heavy rail passenger service previously operated in the early 1900's. Track bed types on the Green line also include embedded, slab, grass, ballast and plinth. The gradient profile of the Green Line is 69 meters in the out-bound direction as detailed in Figure 12 [88].

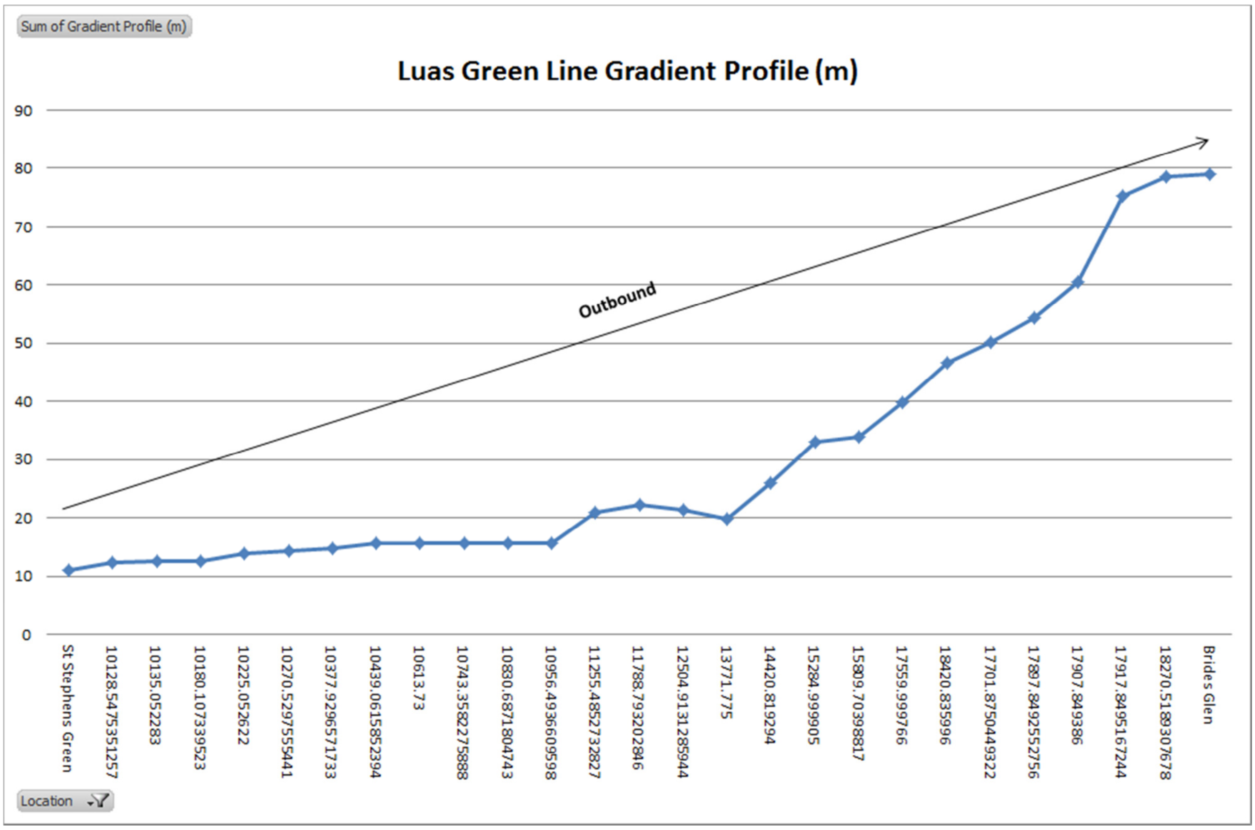


Figure 12: Luas Green Line Gradient Profile

2.2.3 Luas Services

Luas operates passenger service 364 days each year, the 25th of December is the only day that Luas does not operate passenger services. Services begin at approximately 05:30 and finish at 01:25 on both the Red and Green Lines. Unlike traditional heavy rail operations, there is no specific timetable for each tram at each stop. Instead Luas operates set interval headways. This is a set time between each tram vehicle operating on the line. At present there are two headway times. Both AM (06:30-10:00) and PM (15:30-19:00) peak operate headways of between 4 and 10 minutes between trams. Off peak operations which are the times outside the AM and PM peak operate headways of between 10 and 15 minutes between trams. This form of operation is favoured for LRT operations as the lowest travel times for passengers are achieved. To operate this service type the Red line requires 26 vehicles for peak services each day out of a total of 40 trams. The Green line requires 19 tram vehicles for peak service each day out of a total of 26 trams. Annually Luas operates over 2,000,000 km on the Red Line and 1,500,000 km on the Green Line, with over 72,176 hours of service collectively. Road traffic accidents, vehicle or infrastructure faults may cause regulations to services which will deviate from the original timetable. Table 1 indicates the total hours Luas operates [89].

Table 1: Luas Operational Hours

Green Line Operational Hours					
	In Service	Lay Over	Pull In / Out	Preperation	Total
Weekday	189:21:00	34:13:00	06:14:00	07:20:00	237:08:00
Saturday	137:10:00	32:16:00	04:46:00	03:40:00	177:52:00
Sunday	101:02:00	22:46:00	04:38:00	02:40:00	131:06:00
Red Line Operational Hours					
	In Service	Lay Over	Pull In / Out	Preperation	Total
Weekday	329:57:00	60:22:00	12:27:00	11:12:00	413:58:00
Saturday	137:10:00	32:16:00	04:46:00	03:40:00	177:52:00
Sunday	185:09:00	52:41:00	08:28:00	06:49:00	253:07:00

In-service hours are those operated with passengers on-board, layover describes the time spent at the end of the line in the shunt area waiting to depart on the next service. Pull in, Pull out is the time trams consume exiting and entering the depot at the start and end of service respectively. Preparation is the time taken to inspect the vehicle by the driver pre-departure. These times would also include recovery times, where a tram may get delayed on the main line this time can be made back up during the turnaround at the end of each service.

2.3 Luas Network - Technical Aspects

This section of the thesis explains the technical aspects of Luas rolling stock, infrastructure and IT systems used during the operation of the network. The sources of information for this section were original design drawings, engineering manuals and technical specifications provided by Transdev and Alstom.

2.3.1 Luas Electrical Infrastructure

Luas is an electrically powered light rail system. There are a total of twenty sub-stations strategically located around the system to supply the optimal medium voltage DC power to the OCS for use by tram vehicles. There are eleven sub-stations located on the Red Line and nine on the Green line. Alternating current is fed at 10.5 Kilovolt Amp Meters (kVA) from the main national grid into Luas sub-stations. This AC power is then fed through oil filled rectifiers, which inverts the medium voltage AC to a nominal 750 V DC power. Power is controlled by a high speed circuit breaker system and is fed through four parallel feeder cables known as F1, F2, F3 and F4 to both the in-bound and out-bound section of the OCS [90].

Figures 13 shows a line schematic of the traction power distribution system for a section of the Luas Red Line.

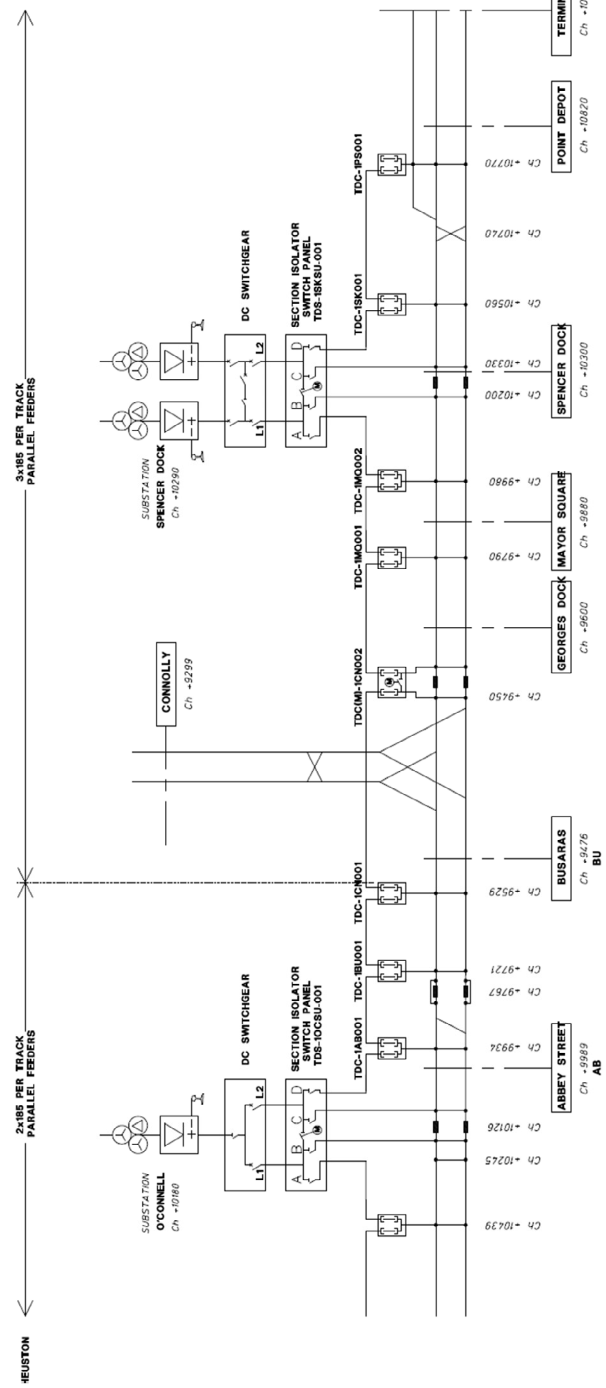


Figure 13: Luas Traction Power Distribution System [90]

Each sub-station is designed to supply power to a designated section of track, these electrical sections are separated by section insulators at regular intervals. When a tram passes through these section insulators, the power it receives is passed from one sub-station to another. Original Luas sub-stations are rated at 1 megawatt (MW), with the later installed sub-stations located on Luas extensions having a greater rating of 1.6 MW which allows for the potential furture increase in passengers services. Sub-stations continuously work to maintain the OCS at a nominal voltage of 750 V DC [90]. This voltage can fluctuate above or below 750 V depending on traffic in the area. Minimum voltage on the OCS is 550 V DC and the maximum is 900 V DC. Luas sub-stations were designed to work over and above the capacity normally required to ensure an uninterrupted supply of power during any operational situation. If power was lost to one sub-station due to a grid power cut or technical fault, this sub-station could be remotely by-passed using the PS Scada system. The two neighbouring sub-stations would then provide power to the electrical section of the sub-station out of service, the entire system has the capacity to operate at N-1 (one sub-station disabled). This creates a failsafe system for Luas, and reduces the risk of disruptions to passenger service. Current from each tram is distributed back through a current return device located on each motor bogie and three wheel-shuns located on each tram wheel-set to the running rails of the system to complete the electrical circuit [90].

2.3.2 Citadis 401 and 402 Tram Vehicles

Luas rolling stock consists of Alstom manufactured light rail vehicles known as Citadis TGA trams. The Red Line operates the Citadis TGA 401 style vehicle. These vehicles are 40 meters in length and can carry between 6 and 8 people per meter squared (ppm²). There are 40 vehicles available for operation on the Red Line [89]. Figure 14 details the configuration of the Citadis 401 tram.

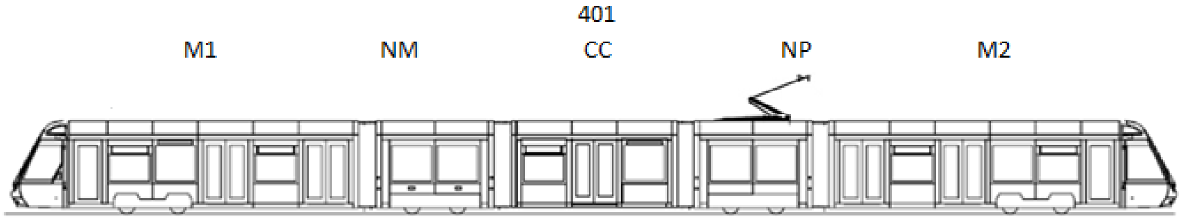


Figure 14: Citadis 401 Style Tram Vehicle [91]

The Luas Green line operates a Citadis TGA 402 style vehicle which is 43 meters in length, and has an extra 2 modules compared with the older 401 vehicles. 402 style vehicles can carry 6 and 8 ppm². The Green line has a total of 26 trams available for operation. Figure 15 details the configuration of the Citadis 402 tram.

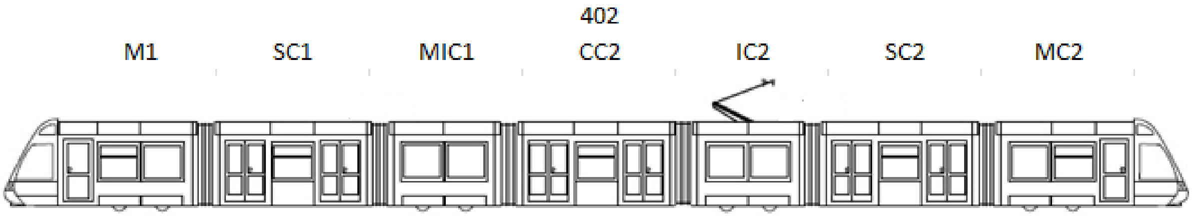


Figure 15: Citadis 402 Style Tram Vehicle [91]

Tram vehicles draw 750 V DC current from the OCS via a pantograph located on the roof of each vehicle. The power passes through the main circuit breaker to the Onix inverter units located on the roof of the tram over each of the three motor bogies. The Onix inverts the DC voltage to AC for use by the traction motors. The Agate power control system then regulates the power, distributing it throughout the vehicle. A percentage of power is used for tram systems such as the heating and ventilation and lighting systems and is regulated by the tram static converter. The static converter unit provides a specific 24 V DC and 380 V AC supply for use by tram systems. Luas vehicles are equipped with regenerative brakes, regenerative braking systems are explained in section 2.4 of Chapter Two. Specifically in case of the Luas, any power generated under braking is distributed back through the chopper unit located within the Onix and can be used in a number of ways as previously outlined. Figure 16 details the Luas tram electrical layout.

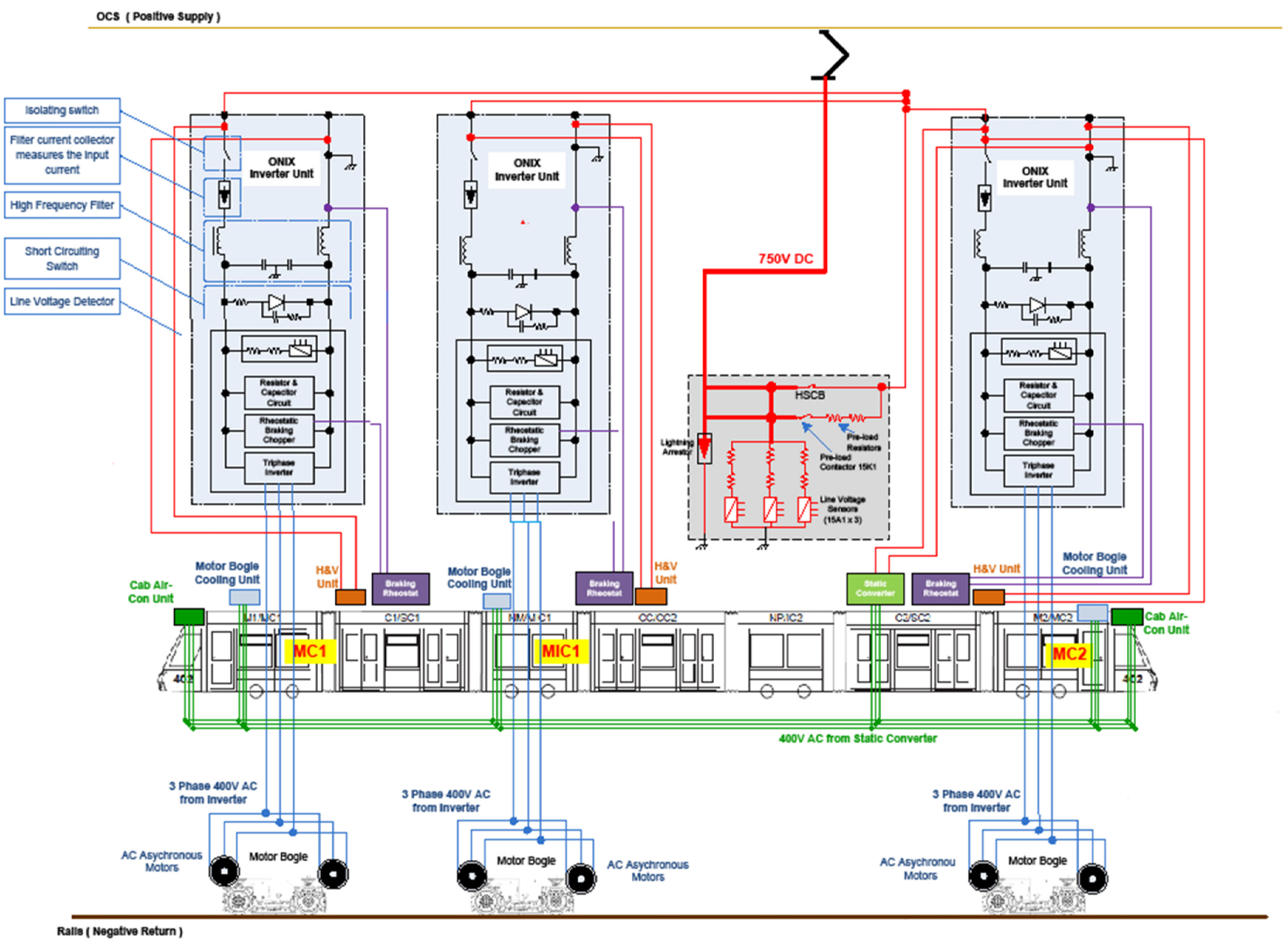


Figure 16: Luas Tram Electrical Layout [92]

2.3.3 Luas Depots

Two maintenance depots located on each line house tram vehicles during non-operational periods and also provide maintenance and office facilities. The Red Line Depot is located at the Red Cow stop and the Green line depot at Sandyford stop. The Red Cow depot has 12 storage lanes which have the capability to store up to 48 trams at 40 m. The depot workshop has six workshop lanes of which 3 have both pit and gantry access for maintenance of the roof and undercarriage of the trams. The Green line depot has eight storage lanes, which have a capability to store 32 trams at 43 m. The depot workshop has three workshop lanes, two of which have pit and gantry access. Trams services originate from each depot in the morning and return to the depot post service. Figure 17 and 18 show the Luas depots.

Figure 17: Luas Sandyford Depot

Figure 18: Luas Red Cow Depot

Each depot also provides office space for Luas contractors and operators. The Red Cow depot incorporates the main central control room and server rooms for Luas IT systems. Power is supplied to the depots by way of the depot sub-stations. 750 V DC medium voltages are supplied to the OCS in the stabling lanes and 400 V AC to office areas. Red Cow and Sandyford depots have the highest consumption of all sub-stations on the Luas system due to the large amount of activity which takes place in these depots.

2.3.4 Luas Stops

Luas has a total of 32 and 22 stops located on the Red and Green Lines respectively. Each Luas stop provides a platform for passengers to board and exit Luas vehicles. Stops also provide essential services to passengers such as ticket machines, passenger information displays, ticket validators, parking meters, signage, seating and shelters, CCTV and lighting. Power is supplied to each Luas stop in one of two ways. The first is by a Luas sub-station, if a sub-station is located adjacent to the stop it will provide the 3-phase 400 V AC supply required to power the non-essential stop systems through an auxiliary supply system. If there is no adjacent sub-station power will be provided directly by the grid passing through an electrical cubicle located adjacent to the stop [90]. Figure 19 details a typical Luas stop and platform.

Figure 19: Luas Platform Layout

Chapter 3: *Methodology*

The main aim of this research is to identify options to reduce the energy consumption of the Luas network. In order to achieve the aims and objectives set out, this research was conducted using a mixed methodology. Both qualitative in the form of an extensive review of literature and quantitative in the form of data collection and analysis methods of research were employed. This Chapter describes the research methodology and details the approach used to collect the relevant data.

3.1 Qualitative Research

The efforts made to identify and reduce energy consumption throughout the light rail industry through efficient operations, modifications to existing systems and the introduction of new technologies were identified and analysed from published literature already available. The sources of this literature include academic papers, industry publications and reports, documentation from European Union lobby groups and rail industry specialist groups. The review and analysis of current available literature is detailed in Chapter 2, section 2.1. In addition to the review of published literature, specific information with regard to the Luas network detailed in Chapter 2, section 2.2 and 2.3 including both operational and technical information were obtained from a review of original design, engineering manuals, technical specifications and contractual documentation.

3.2 Quantitative Research

Quantitative research in the form of data collection, specific testing and analysis formed a large part of this research. In order to reduce energy you must first establish the energy demand. Energy consumption data for the Luas network was obtained from a number of sources and systems. The Meter Registration System Operator (MRSO) is a function of the Electrical Supply Board (ESB) Networks. The MRSO manage data collection and processing from all ESB medium voltage quarter hour sites, these sites include all Luas sub-stations. The MRSO through Transdev provided the quarter hour medium voltage (10.5 kV) energy consumption data for each of the Luas sub-stations. This data was provided on a monthly basis covering the previous month's consumption. A number of system installed throughout the Luas network were utilised as part of this research to gather specific energy consumption data. These systems are detailed in section 3.4 of this Chapter.

Once the raw energy consumption data was collected it required formatting for usability. This formatting was achieved mainly through Microsoft Excel pivot tables and graphs. Once the usable data was available it was analysed against targets and performance standards developed throughout the research. Over the period of this research a large data set of Luas energy consumption was collected which allowed for detailed analysis, trending and setting of targets. This large data set covering over two years will also allow for future evaluation of energy reduction initiatives once fully implemented.

Quantitative research also took the form of specific testing throughout this research. This testing included both aspects of Luas infrastructure and rolling stock. Where possible the energy consumption of the specific component under test was recorded before, throughout and after the testing. Portable energy meters allowed for the specific testing of lighting circuits where lights had been changed to more efficient fittings. An energy metering system installed on one tram operating on the Luas Red Line allowed for specific testing of tram components. Several tests were conducted using this tram to determine the energy consumption of efficient driving styles, the heating and ventilation systems etc.

3.3 Research Limitations

As with all research limitations applied to the methodology. The main limitations encountered during this research included access to data, testing and modification of Luas systems. Data collection was a main feature of this research. In order to accurately estimate energy savings from specific initiatives detailed analysis of the current energy consumption was required. One of the principal sources of Luas energy consumption was through the MRSO. This data was only supplied on a monthly basis which led to delays in analysis. Technical issues surrounding the PS Scada system throughout the research period also led to delays in extracting energy consumption data. Access to a number of Luas low voltage electrical meters proved difficult due to their locations. The meters which are located in the technical room of a sub-station which is underground required a specific permit to access. Confined space training also had to be provided before entry to these locations was permitted. Testing of Luas rolling stock required suitably qualified Transdev staff, availability of rolling stock and possession of the Luas system during non-passengers operations. Coordinating such tests and seeking approval from the safety department of Transdev required time and effort throughout.

3.4 Luas Systems

Similar to all light rail systems, Luas incorporates a number of IT systems which aid in the safe, efficient and reliable operation of the system. These systems which are relevant to this research include Power Systems Scada (PS Scada), Powersoft and the Automatic Vehicle Location System (AVLS). Throughout this research, these systems were utilized by manipulating each to extract the required data during on-going energy monitoring and during specific tests which were carried out to determine the energy consumption of crucial Luas components.

3.4.1 Power Systems Scada (PS Scada)

Power Systems Scada (PS Scada) is a power control and data acquisition system, allowing remote control and monitoring of all aspects of the power systems and electrical infrastructure across the entire Luas system from the main control room, and through maintenance workstations. The system used by Luas was designed and installed by the Portuguese telecommunications and power systems company Efacec. Each sub-station and electrical cubicle is represented on the PS Scada front end IT application. Luas traffic controllers and infrastructure maintainers can actively monitor the power status of the system and remotely control infrastructure components such as opening or closing high-speed circuit breakers, energise or de-energise sub-stations. Traffic controllers also have the ability to shut down the power across the entire system in the event of a safety incident. Users may click on any sub-station on the PS Scada main page mimic. Once a sub-station is selected a mimic will be displayed which presents the live status of the electrical circuit within that sub-station. Figures

20 and 21 show the main PS Scada front end, and the electrical diagram overview for the Red Cow sub-station.

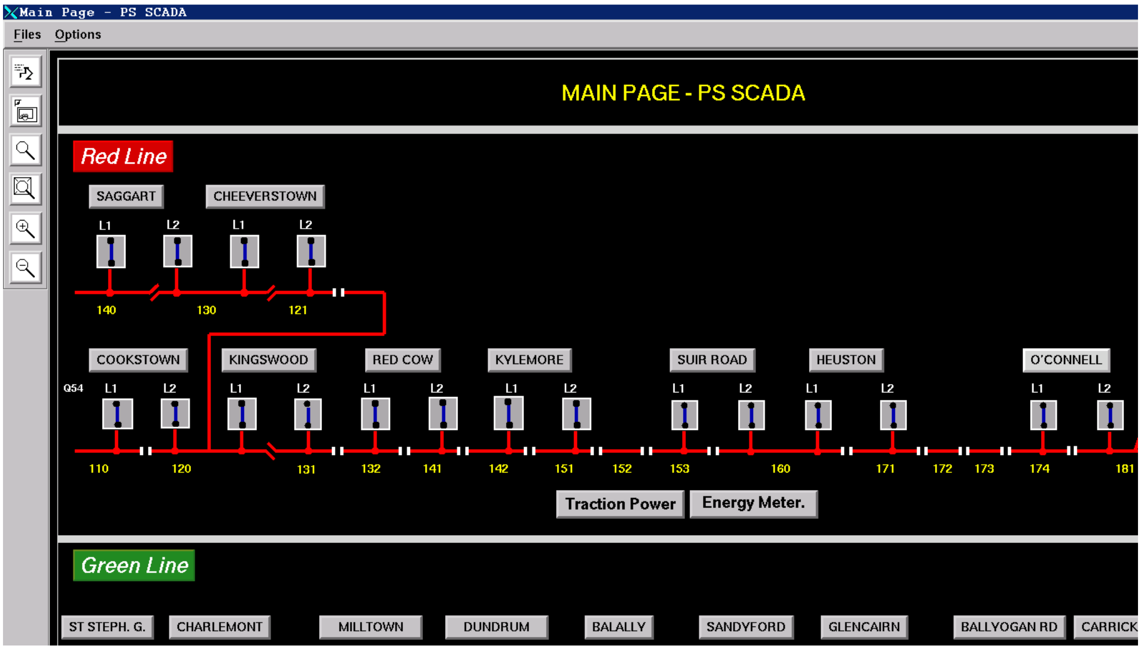


Figure 20: PS Scada Main Page

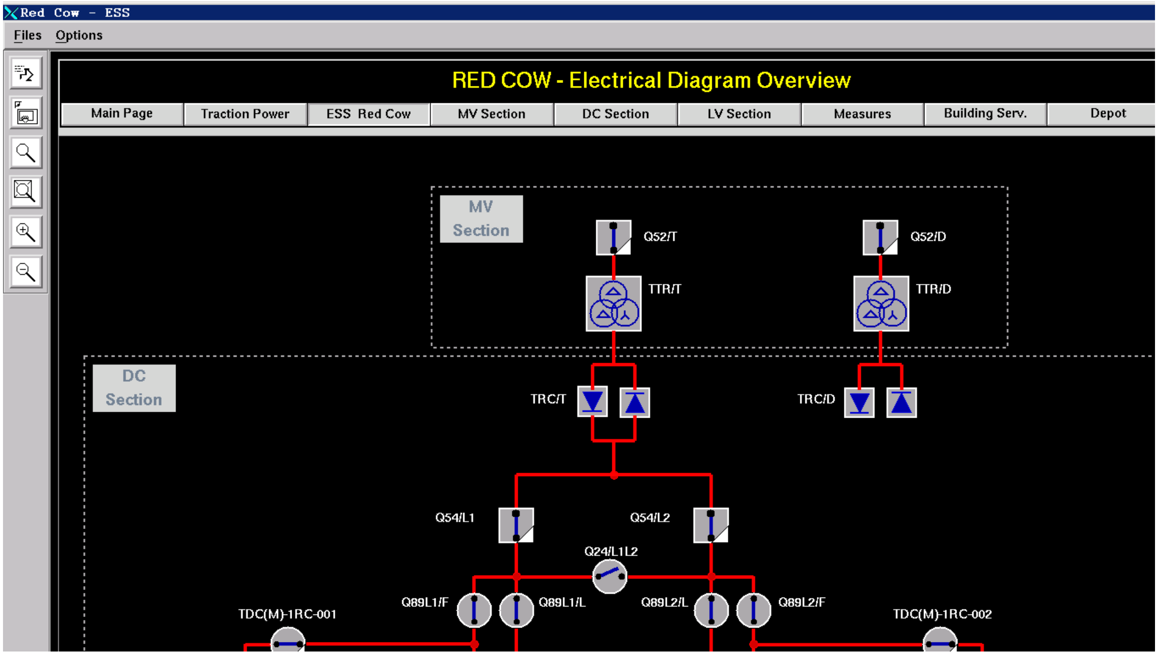
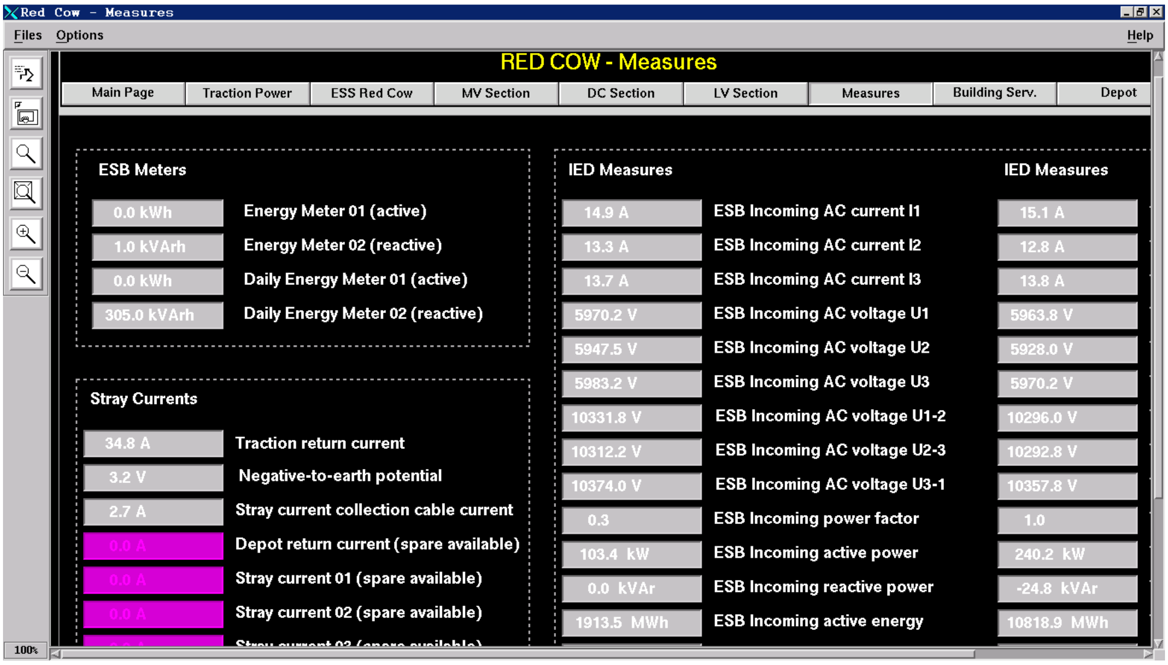


Figure 21: PS Scada Sub-station Electrical Layout

A secondary function of PS Scada is its ability to remotely display live power values which are being metered locally at each sub-station. These values include incoming power (current and voltage), active power output (current and voltage), and return current. This live energy consumption data is visible on the PS Scada front-end application for all sub-stations. The live power readings are also recoded at two minute intervals on servers located in the Red Cow Depot. Historical power reports can then be generated from the main control room. The raw PS Scada data used to generate the reports is stored on Luas servers for a minimum of one year. A number of power entities such as those listed in Figure 22 may be extracted at any time using a Java driven reports application. Figure 22 shows the live meters reading page of the PS Scada system for the Red Cow sub-station and the power entities being metered locally.



ESB Meters

0.0 kWh	Energy Meter 01 (active)
1.0 kVArh	Energy Meter 02 (reactive)
0.0 kWh	Daily Energy Meter 01 (active)
305.0 kVArh	Daily Energy Meter 02 (reactive)

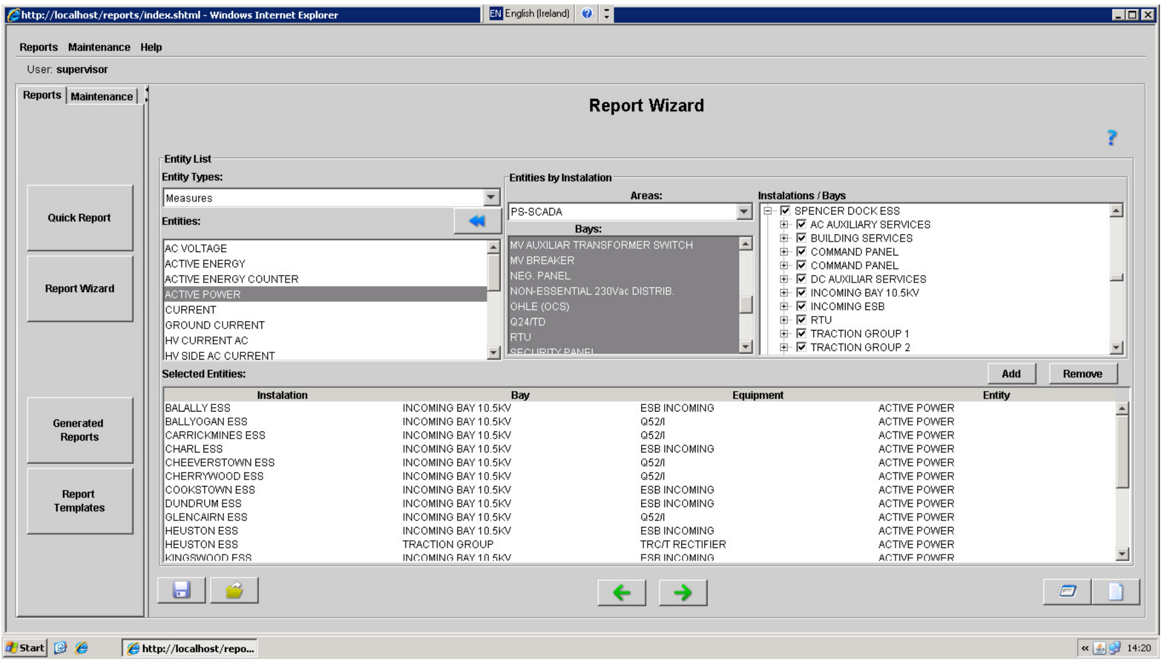
Stray Currents

34.8 A	Traction return current
3.2 V	Negative-to-earth potential
2.7 A	Stray current collection cable current
0.0 A	Depot return current (spare available)
0.0 A	Stray current 01 (spare available)
0.0 A	Stray current 02 (spare available)
	Stray current 03 (spare available)

IED Measures		IED Measures
14.9 A	ESB Incoming AC current I1	15.1 A
13.3 A	ESB Incoming AC current I2	12.8 A
13.7 A	ESB Incoming AC current I3	13.8 A
5970.2 V	ESB Incoming AC voltage U1	5963.8 V
5947.5 V	ESB Incoming AC voltage U2	5928.0 V
5983.2 V	ESB Incoming AC voltage U3	5970.2 V
10331.8 V	ESB Incoming AC voltage U1-2	10296.0 V
10312.2 V	ESB Incoming AC voltage U2-3	10292.8 V
10374.0 V	ESB Incoming AC voltage U3-1	10357.8 V
0.3	ESB Incoming power factor	1.0
103.4 kW	ESB Incoming active power	240.2 kW
0.0 kVAr	ESB Incoming reactive power	-24.8 kVAr
1913.5 MWh	ESB Incoming active energy	10818.9 MWh

Figure 22: PS Scada Live Meter Readings

Prior to this research the historic reports application of the PS Scada system had not been fully utilised by Luas and lay dormant. As a consequence no user manuals or technical support was available for the reports application aspect. With the potential valuable data available from the system, it was decided to utilise the PS Scada system. This required significant self-training, and manipulation of the system to export reliable data. Report templates were created for a number of power entities including incoming power (10.5 kVa) and active power (kW). The data exported from PS Scada was then evaluated and confirmed to be correct when compared to the energy supplier usage data. Once the accuracy of the data was confirmed, by cross referencing the daily medium voltage energy consumption totals (kWh) for each sub-station from PS Scada with the MRSO data (kWh) the system was set up to run automatic reports on a daily basis. These reports were then extracted on a weekly basis and analysed as part of the on-going energy monitoring throughout this research. Figure 23 shows the report application within PS Scada which was used to extract daily energy consumption data.



User: supervisor

Entity Types: Measures

Entities: ACTIVE POWER

Areas: PS-SCADA

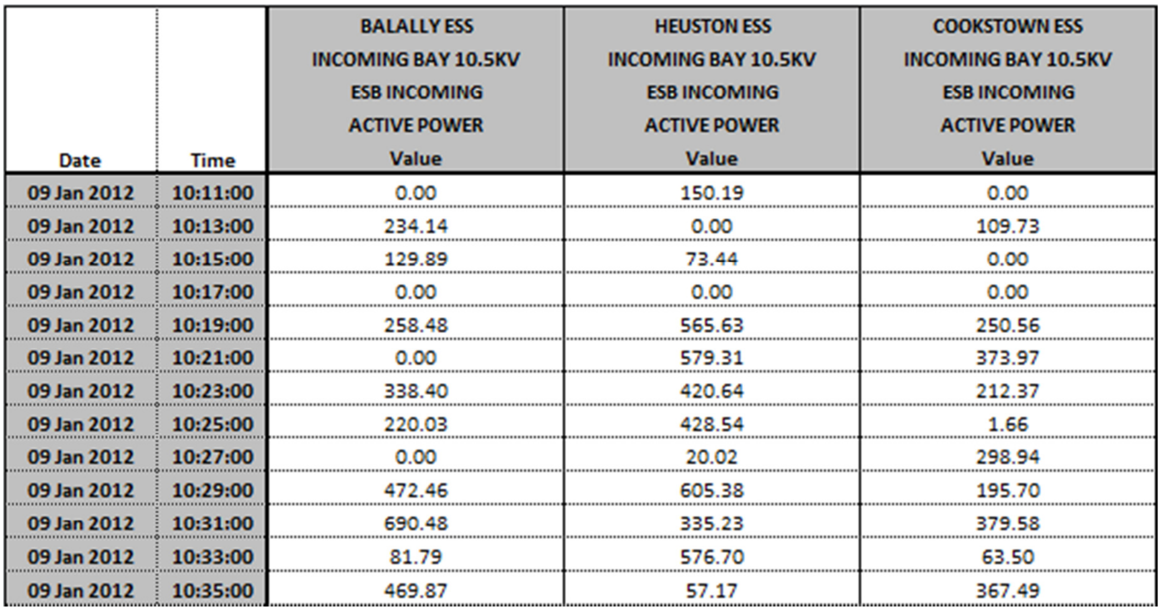
Selected Entities:

Instalation	Bay	Equipment	Entity
BALALLY ESS	INCOMING BAY 10.5KV	ESB INCOMING	ACTIVE POWER
BALLYOGAN ESS	INCOMING BAY 10.5KV	Q52/I	ACTIVE POWER
CARRICKMINES ESS	INCOMING BAY 10.5KV	Q52/I	ACTIVE POWER
CHARL ESS	INCOMING BAY 10.5KV	ESB INCOMING	ACTIVE POWER
CHEEVERSTOWN ESS	INCOMING BAY 10.5KV	Q52/I	ACTIVE POWER
CHERRYWOOD ESS	INCOMING BAY 10.5KV	Q52/I	ACTIVE POWER
COOKSTOWN ESS	INCOMING BAY 10.5KV	ESB INCOMING	ACTIVE POWER
DUNDRUM ESS	INCOMING BAY 10.5KV	ESB INCOMING	ACTIVE POWER
GLENCAIRN ESS	INCOMING BAY 10.5KV	Q52/I	ACTIVE POWER
HEUSTON ESS	INCOMING BAY 10.5KV	ESB INCOMING	ACTIVE POWER
HEUSTON ESS	TRACTION GROUP	TRC/T RECTIFIER	ACTIVE POWER
KINGSWOOD ESS	INCOMING BAY 10.5KV	ESB INCOMING	ACTIVE POWER

Figure 23: PS Scada Reports Application

One of the principal reports generated was incoming power AC and the subsequent DC supply of each Luas sub-stations. This raw data came in the form of two-minute interval live readings of the incoming 10.5 KVA meter, and the two DC feeder cables through the Q52 breakers. Table 2 details the raw data file extracted from PS Scada for Balally, Heuston and Cookstown sub-stations.

Table 2: PS Scada Excel Report



Date	Time	BALALLY ESS INCOMING BAY 10.5KV ESB INCOMING ACTIVE POWER Value	HEUSTON ESS INCOMING BAY 10.5KV ESB INCOMING ACTIVE POWER Value	COOKSTOWN ESS INCOMING BAY 10.5KV ESB INCOMING ACTIVE POWER Value
09 Jan 2012	10:11:00	0.00	150.19	0.00
09 Jan 2012	10:13:00	234.14	0.00	109.73
09 Jan 2012	10:15:00	129.89	73.44	0.00
09 Jan 2012	10:17:00	0.00	0.00	0.00
09 Jan 2012	10:19:00	258.48	565.63	250.56
09 Jan 2012	10:21:00	0.00	579.31	373.97
09 Jan 2012	10:23:00	338.40	420.64	212.37
09 Jan 2012	10:25:00	220.03	428.54	1.66
09 Jan 2012	10:27:00	0.00	20.02	298.94
09 Jan 2012	10:29:00	472.46	605.38	195.70
09 Jan 2012	10:31:00	690.48	335.23	379.58
09 Jan 2012	10:33:00	81.79	576.70	63.50
09 Jan 2012	10:35:00	469.87	57.17	367.49

The incoming power is the power that each sub-station is supplied from the electrical grid for use as 750 V DC on the overhead centenary line. The data which was extracted from the reports application was unusable in its raw format and had to be further manipulated into real quantifiable data. This was achieved by averaging the two minute live readings over a fifteen minute period to match the Meter Registration System Operator energy consumption format. This was achieved using an excel macros formula, once the data was averaged over a fifteen minute period it could then be graphed and quantified in line with suppliers formats. The advantages of having this data on a daily basis, was that monitoring could be achieved at a fraction of the time period, allowing irregularities to be identified much quicker. The main reason for exporting this data was to analyse energy consumption levels at each sub-station. Reports were exported from the PS Scada system on a daily basis throughout the research, where the data for the previous week was reviewed and analysed. This was also the first time Luas had a daily break down of energy consumption, as Luas previously relied on the Meter Registration System Operator providing data which was only supplied each second month. The data was also essential for quantifying any energy reduction initiatives which were implemented as a result of this research. Over two years' worth of Luas energy consumption data (from 2011 to 2014) have been collected and analysed during this research. This has allowed for determining possible savings from energy reduction initiatives identified and implemented. Transdev have continued to generate energy reports from PS Scada on a daily basis to monitor and analyse energy consumption across the system.

3.4.2 Powersoft Vehicle and Depot Metering System

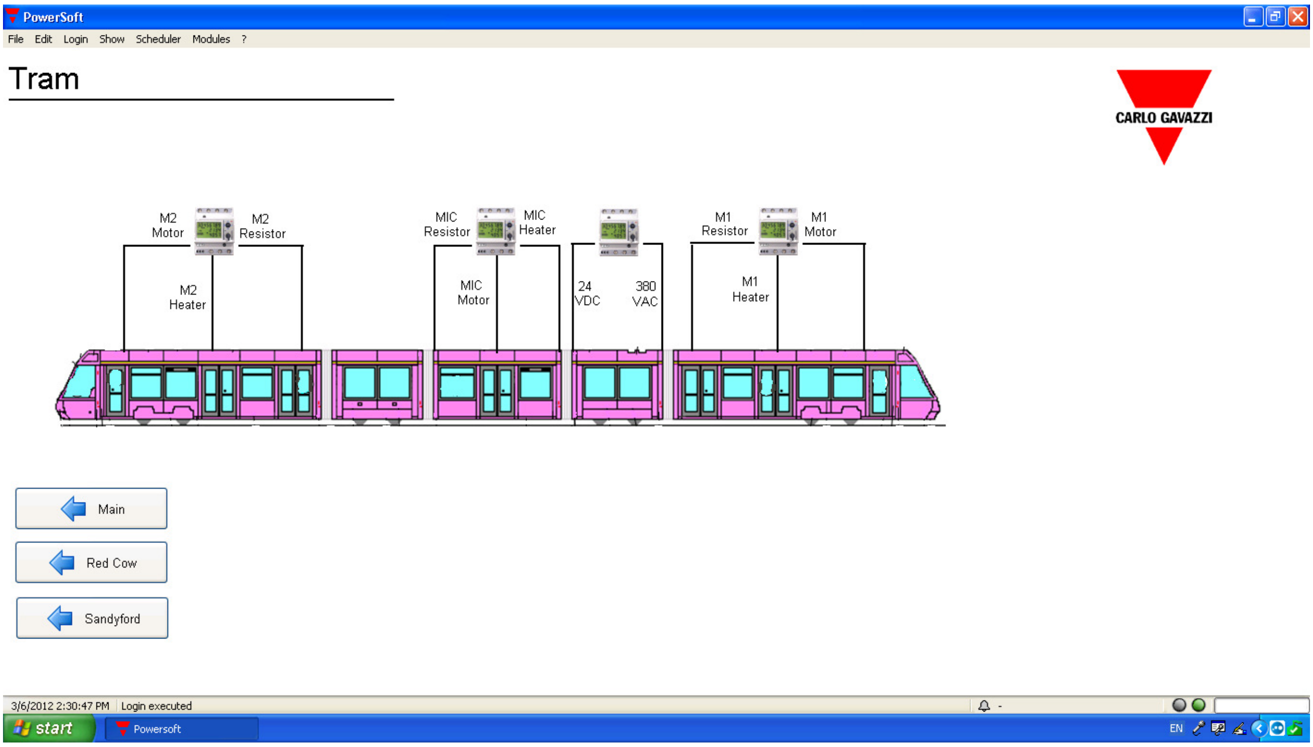
Powersoft is an analysis platform designed to act as a front end energy management system. The system was installed by Transdev in 2010 to aid in the reduction of energy across the system. Energy meters, data loggers and GSM transmitters were installed on key components of Luas infrastructure and rolling stock. Powersoft also incorporates a server and software system which allows for live energy consumption viewing and historical report generation. Transdev initially installed Powersoft on one tram operating on the Luas Red Line. The aim was to meter the key energy consuming components of the tram to gain a better understanding of energy consumption usage of Luas vehicles. A total of four meters were installed on the Luas tram (Tram No: 3010 on the Red Line). The meters used were Carlo Gavazzi EM24 energy analysers. The meters have the ability to record energy consumption, which is then transmitted through a GSM device on the roof of the tram back to the central server. Each meter has the capacity to measure three separate values. Table 3 outlines the location and function of each of the tram based meters.

Table 3: Location of Tram Meters

Tram Component	Tram Location	Quantity of Meters	Meter Type
Traction Motors	M1/MIC/M2	3	3 Phase AC
Heater Resistors	M1/MIC/M2	3	750 V DC
Braking Rheostats	M1/MIC/M2	3	750 V DC
Static Converters	MIC	2	400 V AC / 24 V DC

The AC meters located on the traction bogies are three phase coil meters which were installed to each phase of the motor input cables. Both current and voltage are measured, which allows for the calculation of a kW energy consumption figure. The direct current meters used for the heating, rheostats and static converter are DC shunts. These shunts also measure both current and voltage producing a kWh energy consumption figure. Data was remotely transmitted from the tram meters via a GSM unit using a virtual private network and a subscriber identity module card to the base software system. The system allowed for accurate monitoring of tram energy consumption, down to each individual motors bogies, something previously unavailable for operational trams. Within the software package Powersoft allowed the user to access the historical data. Data could be viewed in real time at 21 second intervals and reports could be generated at one minute intervals. The real time live data (21 second intervals) was not required for the reports generated throughout this research, the one minute interval reports were primarily used. This level of detail allowed for accurate analysis of tram based energy consumption. With the use of such a system it was possible to clearly identify the differences in energy consumption during peak and off peak operations, winter and summer operations and differences in driving styles between different drivers. Powersoft was utilised throughout the research to monitor different driver's energy consumption and also used during a number of specific tests to assess the impact of pre-determined driving styles.

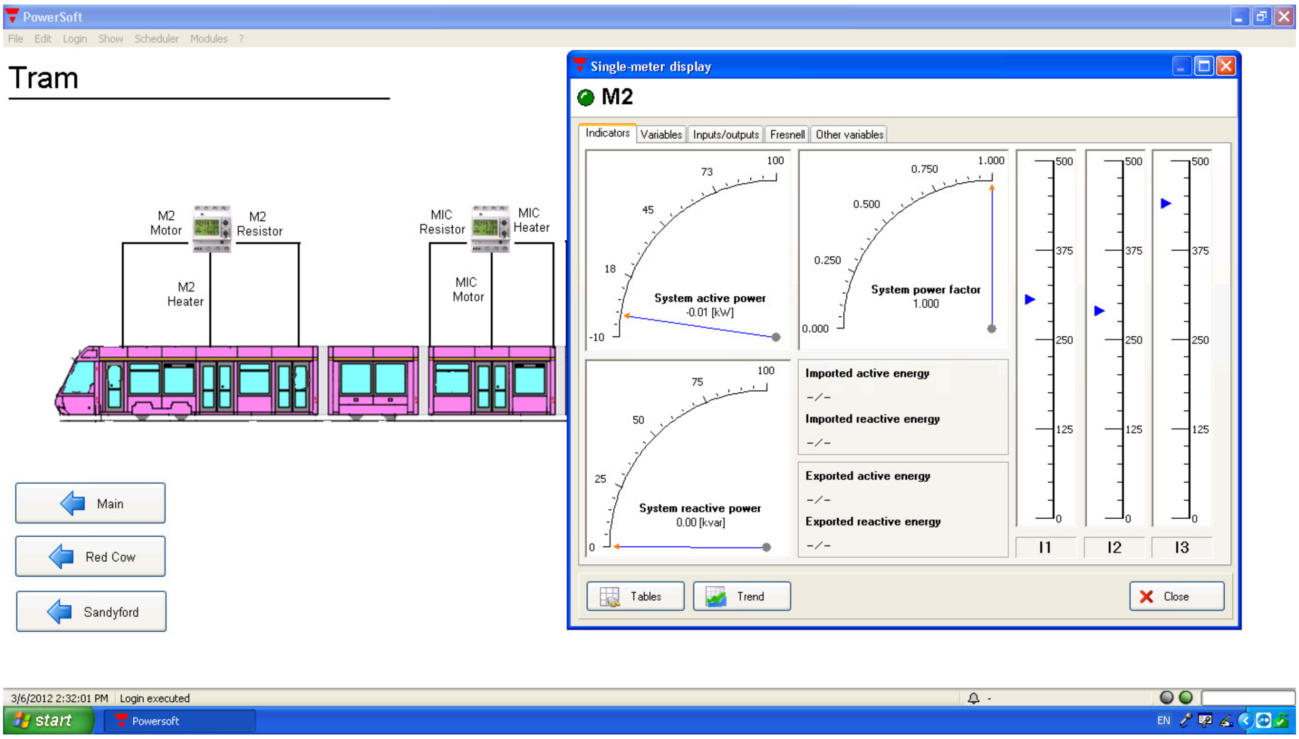
Figure 24 shows the Powersoft tram front. From here the user can select any of the meters installed on tram 3010 to view live power readings.



3/6/2012 2:30:47 PM Login executed

Figure 24: Powersoft Tram Front End Application

Figure 25 details the live power readings for the M2 motor of tram number 3010 operating on the Red Line. Current across the three phases is displayed as well as the live active power of the motor.



System active power
-0.01 [kW]

System power factor
1.000

System reactive power
0.00 [kvar]

Imported active energy
-/-

Imported reactive energy
-/-

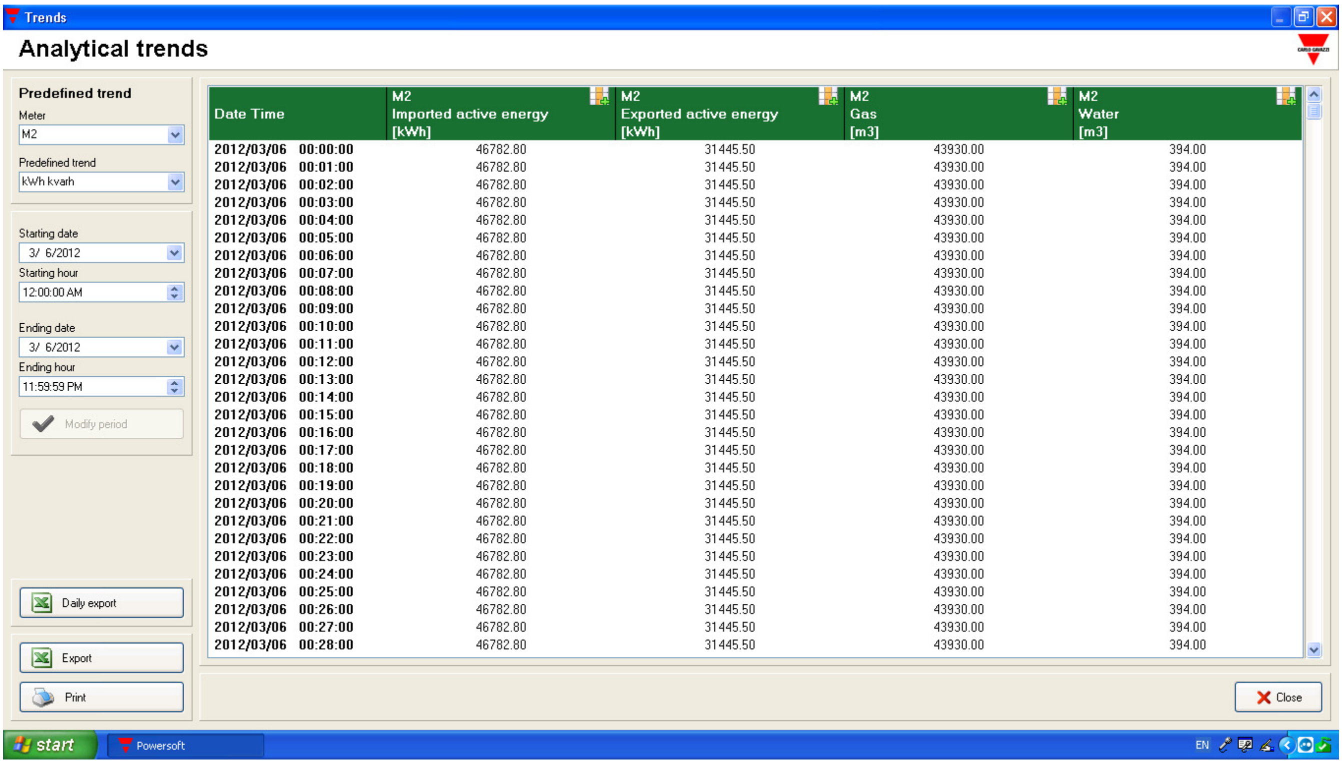
Exported active energy
-/-

Exported reactive energy
-/-

3/6/2012 2:32:01 PM Login executed

Figure 25: Powersoft Live Meter Readings – M2 Motor

Figure 26 shows the reporting application associated with the Powersoft system. Historical reports can be generated for all the meters installed on the tram. In this report the total cumulative power imported under traction and exported during braking is displayed in kilowatt hours, at one minute intervals.



Predefined trend
Meter: M2
Predefined trend: kWh kvarh
Starting date: 3/ 6/2012
Starting hour: 12:00:00 AM
Ending date: 3/ 6/2012
Ending hour: 11:59:59 PM

Date Time	M2 Imported active energy [kWh]	M2 Exported active energy [kWh]	M2 Gas [m3]	M2 Water [m3]
2012/03/06 00:00:00	46782.80	31445.50	43930.00	394.00
2012/03/06 00:01:00	46782.80	31445.50	43930.00	394.00
2012/03/06 00:02:00	46782.80	31445.50	43930.00	394.00
2012/03/06 00:03:00	46782.80	31445.50	43930.00	394.00
2012/03/06 00:04:00	46782.80	31445.50	43930.00	394.00
2012/03/06 00:05:00	46782.80	31445.50	43930.00	394.00
2012/03/06 00:06:00	46782.80	31445.50	43930.00	394.00
2012/03/06 00:07:00	46782.80	31445.50	43930.00	394.00
2012/03/06 00:08:00	46782.80	31445.50	43930.00	394.00
2012/03/06 00:09:00	46782.80	31445.50	43930.00	394.00
2012/03/06 00:10:00	46782.80	31445.50	43930.00	394.00
2012/03/06 00:11:00	46782.80	31445.50	43930.00	394.00
2012/03/06 00:12:00	46782.80	31445.50	43930.00	394.00
2012/03/06 00:13:00	46782.80	31445.50	43930.00	394.00
2012/03/06 00:14:00	46782.80	31445.50	43930.00	394.00
2012/03/06 00:15:00	46782.80	31445.50	43930.00	394.00
2012/03/06 00:16:00	46782.80	31445.50	43930.00	394.00
2012/03/06 00:17:00	46782.80	31445.50	43930.00	394.00
2012/03/06 00:18:00	46782.80	31445.50	43930.00	394.00
2012/03/06 00:19:00	46782.80	31445.50	43930.00	394.00
2012/03/06 00:20:00	46782.80	31445.50	43930.00	394.00
2012/03/06 00:21:00	46782.80	31445.50	43930.00	394.00
2012/03/06 00:22:00	46782.80	31445.50	43930.00	394.00
2012/03/06 00:23:00	46782.80	31445.50	43930.00	394.00
2012/03/06 00:24:00	46782.80	31445.50	43930.00	394.00
2012/03/06 00:25:00	46782.80	31445.50	43930.00	394.00
2012/03/06 00:26:00	46782.80	31445.50	43930.00	394.00
2012/03/06 00:27:00	46782.80	31445.50	43930.00	394.00
2012/03/06 00:28:00	46782.80	31445.50	43930.00	394.00

Figure 26: Powersoft Energy Consumption Report

Powersoft was also installed in both Luas depots at the Red Cow and Sandyford on key infrastructure components. These components included the depot maintenance lighting circuit, the park and ride lighting circuit, the tram sanding and tram wash compressor circuit, and the main office 400 V power supply. Carlo Gavazzi EM24 energy analysers were installed to measure the energy consumption of each of these components. Depending on the location some of these circuits were hard wired back to the central server, where others in more remote locations used GSM transmitters to send the data. Figure 27 displays the distribution board for each of the meters installed at the Red Cow Depot.

Figure 27: Powersoft Distribution Board

Figure 28 shows the Powersoft depot front end. Each of the circuits metered are accessible through the Powersoft application. Both live and historical energy consumption and reports can be accessed at any time similar to that of the tram meters.

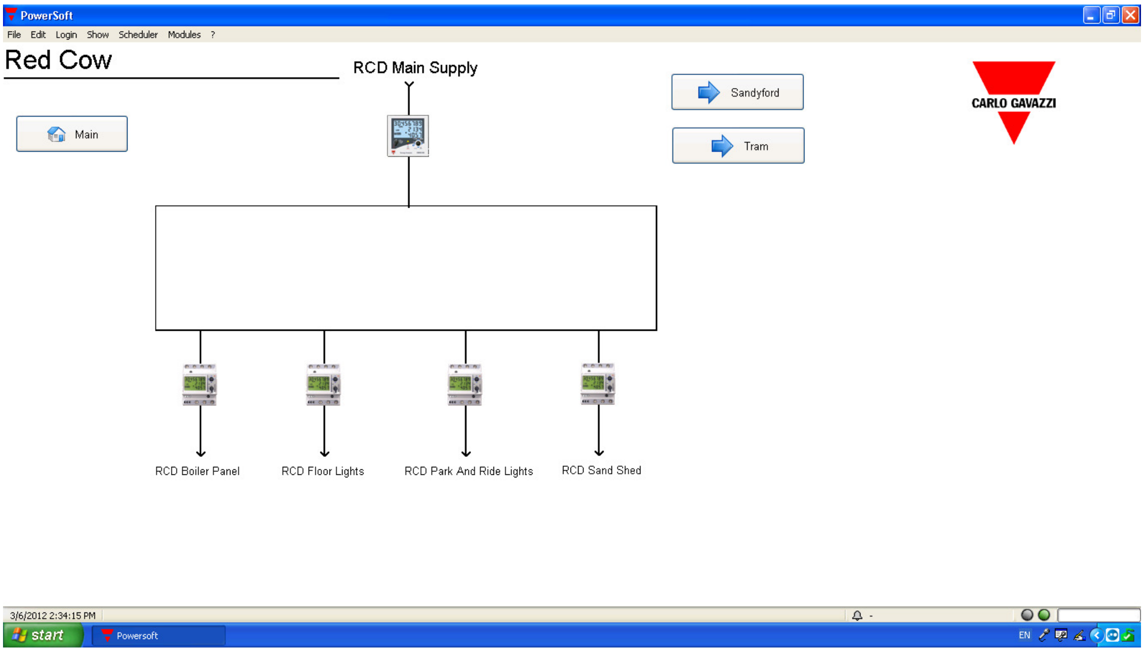


Figure 28: Powersoft Depot Meters Front End

The depot Powersoft system provided both live and historical energy consumption data for the key components in both Luas depots. As part of this research two years of data was compiled and analysed. This data was used to determine potential savings to be made from energy reduction initiatives such as the fitting of new energy efficient lights in the depot maintenance area or the installation of more efficient compressors in the depot workshop.

3.4.3 Automatic Vehicle Location System

The Automatic Vehicle Location System was another tool that was used as part of this research. The AVLS provides location information of the trams operating along each of the two Luas lines and within the depots. Electrical loops fitted at regular intervals within the track bed receive signals transmitted from a transponder located under the driver’s cab of each vehicle as they pass over the loops. Real time data on tram locations and headways between trams are portrayed back to the central control room on the front end display. This AVLS system was used during the tests phase of the research to located trams at set points along the track. It was also used to determine average speed and total run times of trams during testing and during normal passenger service operations. Figure 29 shows the AVLS interface for the Red Line. The interface is a graphical display representing each tram operating on the Red Line. This graphical front end provides information including the tram number, the passenger service number, the location of the vehicle on the track and live headway details for each tram (detailing if the tram is ahead, behind or on schedule as per the timetable). Luas traffic controllers use the AVLS on an on-going basis to monitor and manage the tramway.

The AVLS data regarding trams locations, headways etc is also stored for a minimum of one year on Luas servers. Historical reports can be generated at any time to determine the location of a specific tram on either the Red or Green line or to determine the length of time taken for a tram to complete a journey or specific section of the line.

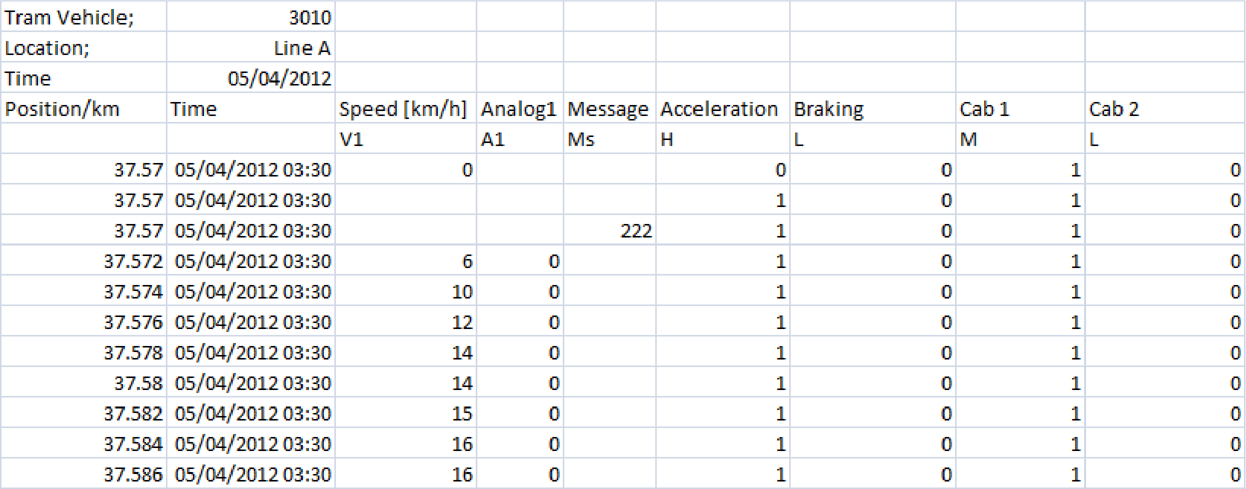
User	Timestamp	Zone	Object type	OIC	Description	Status	Ack/Need Ack	Beep
System	03.06.2012 14:36:12	Red Cow Central Contro...	TmTram	5025	Tram5025 - AH Activate ...	Spot	⚠	
System	03.06.2012 14:35:59	Red Cow Central Contro...	TmTram	3001	Tram 3001 - DRIVER LO...	Spot		
System	03.06.2012 14:35:59	Red Cow Central Contro...	Amos Radio Controller	Radio	Amos Radio - Radio mes...	Spot		
System	03.06.2012 14:35:21	Red Cow Central Contro...	TmTram	5021	Tram5021 - DH Deactiva...	Spot	⚠	

Figure 29: Automatic Vehicle Location System Luas Red Line

3.4.4 Tram Tachometer System

The Tram Tachometer system (Tacho) similar to that fitted to heavy goods vehicles records information including the master controller position (acceleration or braking), tram speed, and cab direction. The system was used during this research and in particular during tram testing. Data from the Tacho was linked with both Powersoft and PS-Scada energy consumption data to determine the amount of energy consumed during specific tram tests. Raw data from the tram Tacho came in graphical form and had to be manually manipulated into an excel format to plot against energy graphs. Table 4 shows the Tacho information for tram number 3010 in excel format.

Table 4: Tram 3010 Tacho download



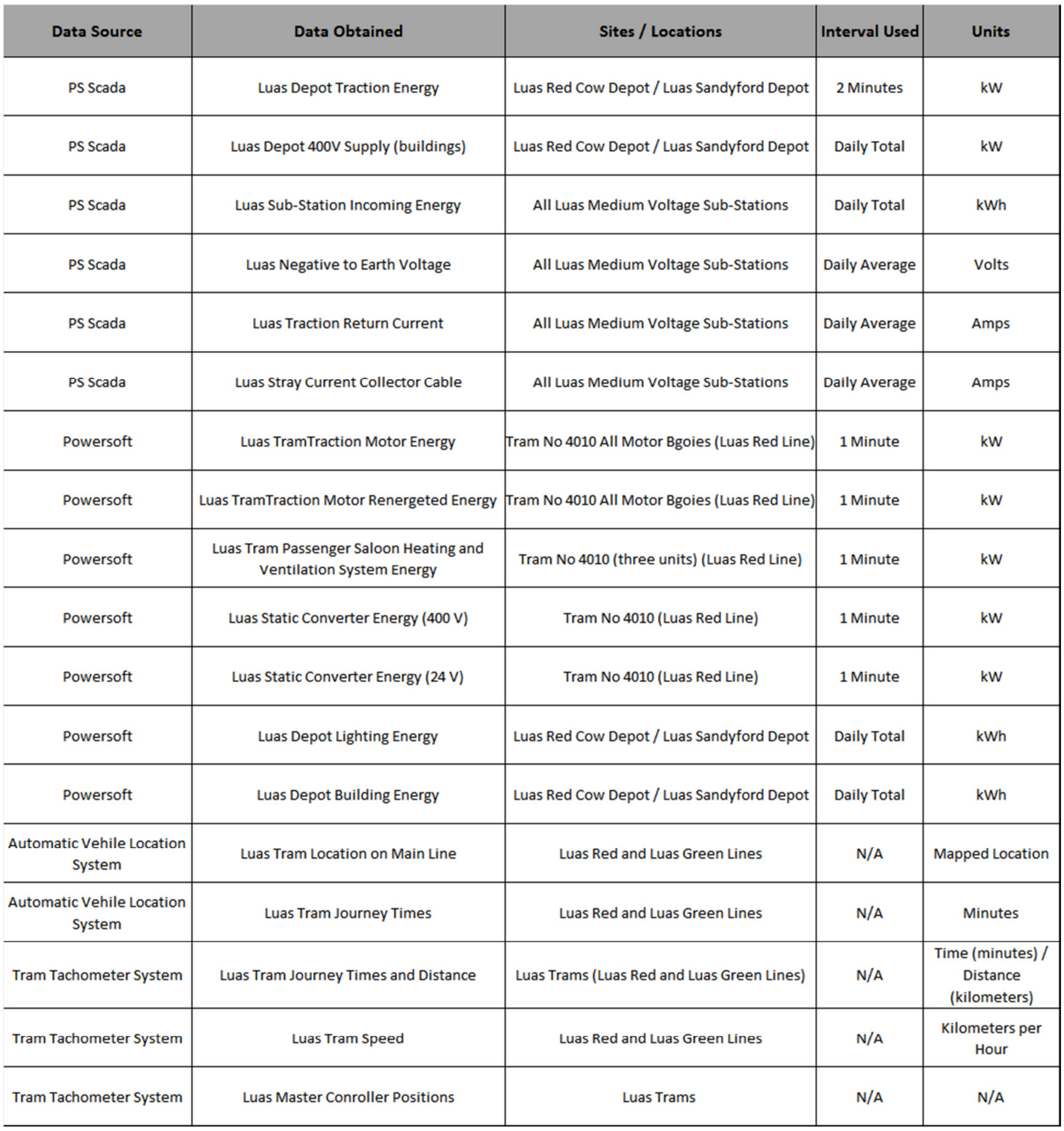
Tram Vehicle;	3010							
Location;	Line A							
Time	05/04/2012							
Position/km	Time	Speed [km/h]	Analog1	Message	Acceleration	Braking	Cab 1	Cab 2
		V1	A1	Ms	H	L	M	L
37.57	05/04/2012 03:30	0			0	0	1	0
37.57	05/04/2012 03:30				1	0	1	0
37.57	05/04/2012 03:30			222	1	0	1	0
37.572	05/04/2012 03:30	6	0		1	0	1	0
37.574	05/04/2012 03:30	10	0		1	0	1	0
37.576	05/04/2012 03:30	12	0		1	0	1	0
37.578	05/04/2012 03:30	14	0		1	0	1	0
37.58	05/04/2012 03:30	14	0		1	0	1	0
37.582	05/04/2012 03:30	15	0		1	0	1	0
37.584	05/04/2012 03:30	16	0		1	0	1	0
37.586	05/04/2012 03:30	16	0		1	0	1	0

These IT systems provided vital detailed data throughout this research. The information extracted from each system was used in conjunction with specific tests and for on-going energy consumption analysis. More details on the use of the data extracted from each system are described in the proceeding chapters.

3.4.5 Summary of Primary Data Sources

Having access to Luas systems throughout this research aided greatly in gathering the required data to determine and analyse Luas energy consumption. All Luas systems which had the potential to provide relevant data were exploited. Table 5 summarises the data sources, the relevant information gathered form each source, the interval and the unit of data.

Table 5: Summary of Data Sources



Data Source	Data Obtained	Sites / Locations	Interval Used	Units
PS Scada	Luas Depot Traction Energy	Luas Red Cow Depot / Luas Sandyford Depot	2 Minutes	kW
PS Scada	Luas Depot 400V Supply (buildings)	Luas Red Cow Depot / Luas Sandyford Depot	Daily Total	kW
PS Scada	Luas Sub-Station Incoming Energy	All Luas Medium Voltage Sub-Stations	Daily Total	kWh
PS Scada	Luas Negative to Earth Voltage	All Luas Medium Voltage Sub-Stations	Daily Average	Volts
PS Scada	Luas Traction Return Current	All Luas Medium Voltage Sub-Stations	Daily Average	Amps
PS Scada	Luas Stray Current Collector Cable	All Luas Medium Voltage Sub-Stations	Daily Average	Amps
Powersoft	Luas TramTraction Motor Energy	Tram No 4010 All Motor Bgoies (Luas Red Line)	1 Minute	kW
Powersoft	Luas TramTraction Motor Renergeted Energy	Tram No 4010 All Motor Bgoies (Luas Red Line)	1 Minute	kW
Powersoft	Luas Tram Passenger Saloon Heating and Ventilation System Energy	Tram No 4010 (three units) (Luas Red Line)	1 Minute	kW
Powersoft	Luas Static Converter Energy (400 V)	Tram No 4010 (Luas Red Line)	1 Minute	kW
Powersoft	Luas Static Converter Energy (24 V)	Tram No 4010 (Luas Red Line)	1 Minute	kW
Powersoft	Luas Depot Lighting Energy	Luas Red Cow Depot / Luas Sandyford Depot	Daily Total	kWh
Powersoft	Luas Depot Building Energy	Luas Red Cow Depot / Luas Sandyford Depot	Daily Total	kWh
Automatic Vehile Location System	Luas Tram Location on Main Line	Luas Red and Luas Green Lines	N/A	Mapped Location
Automatic Vehile Location System	Luas Tram Journey Times	Luas Red and Luas Green Lines	N/A	Minutes
Tram Tachometer System	Luas Tram Journey Times and Distance	Luas Trams (Luas Red and Luas Green Lines)	N/A	Time (minutes) / Distance (kilometers)
Tram Tachometer System	Luas Tram Speed	Luas Red and Luas Green Lines	N/A	Kilometers per Hour
Tram Tachometer System	Luas Master Conroller Positions	Luas Trams	N/A	N/A

Chapter 4: *Luas Energy Consumption: Test Results and Analysis*

4.1 Rolling Stock

The main components of Luas rolling stock energy consumption include the traction motors, the passenger heating and ventilation systems, the drivers cab air conditioning unit, lighting and the on-board computer systems. In order to establish energy reductions with these systems, the energy demand of each area had to be first established.

4.1.1 Traction Motors

The core business of Luas is to provide a safe and reliable transport system. Power to move a Luas vehicle is provided by traction motors located on the three motor bogies of each tram vehicle. Luas trams are equipped with four bogies, three of which are motorised bogies located on the M1, NM and M2 modules of the vehicle, the bogie on the NP section of the vehicle is known as a trailer bogie and has no traction motors as shown in Figure 30.

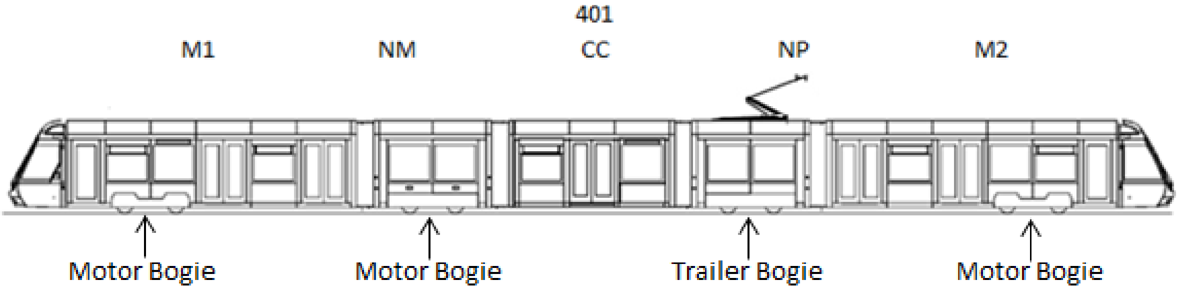


Figure 30: Luas 401 Bogie Configuration [91]

There are two types of motor bogies fitted to the 401 style Luas vehicles. The LHB (high floor motor bogie) motor bogie is fitted to the M1 and M2 sections of the vehicle and an Arpeggeo (low floor running gear) motor bogie is fitted to the NP section. The LHB high floor motor bogie comprises of two traction electric motors, which are located inside the bogie housing. Each axle of the LHB motor bogie is driven by a three-phase alternating AC motor. A solid forged axle is coupled to the motor shaft via a set of fender couplings around the axle. The axle transition radius houses the elastic train set wheels of the vehicle as illustrated in Figure 31.

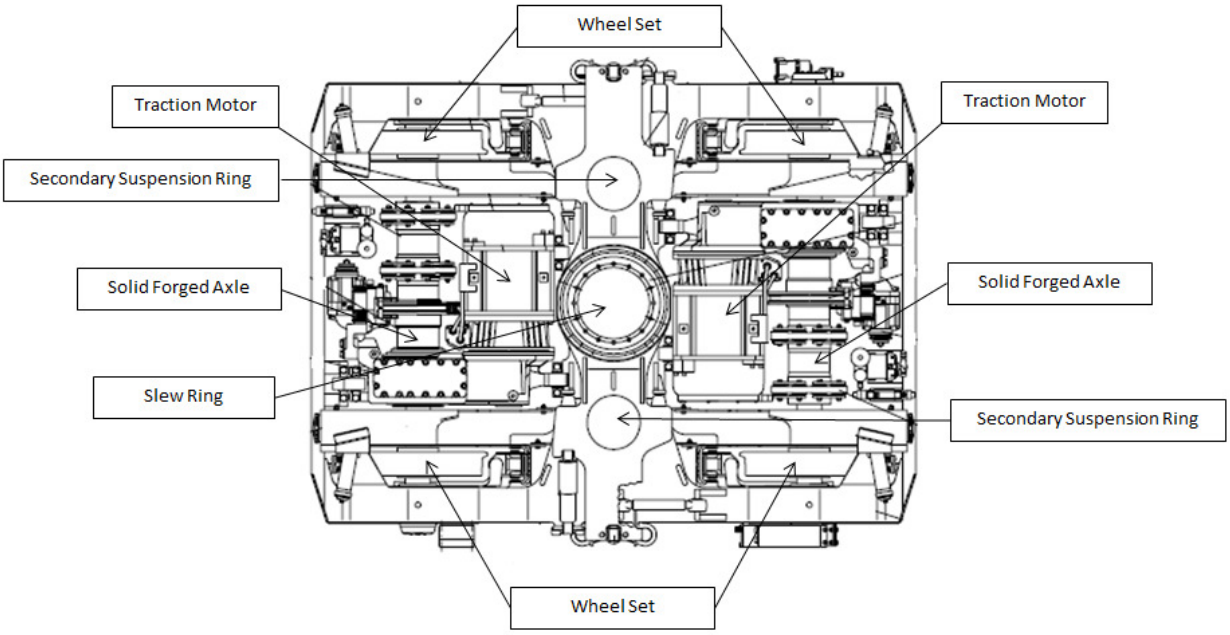


Figure 31: Schematic of Luas LHB Motor Bogie [93]

The Arpeggeo low floor motor bogie consists of an articulated bogie frame of two "L" sections. These "L" sections are a rigid assembly made up of a motor bridge, acting as an axle, and a sole bar. Each axle is driven by a three-phase motor, assembled laterally on the exterior of the motor bridge, and via a two-stage reduction gear. The motor is cooled by Glycolated water fed by the cooling system located on the roof section NM. Figure 32 shows a schematic of the Arpeggeo bogie.

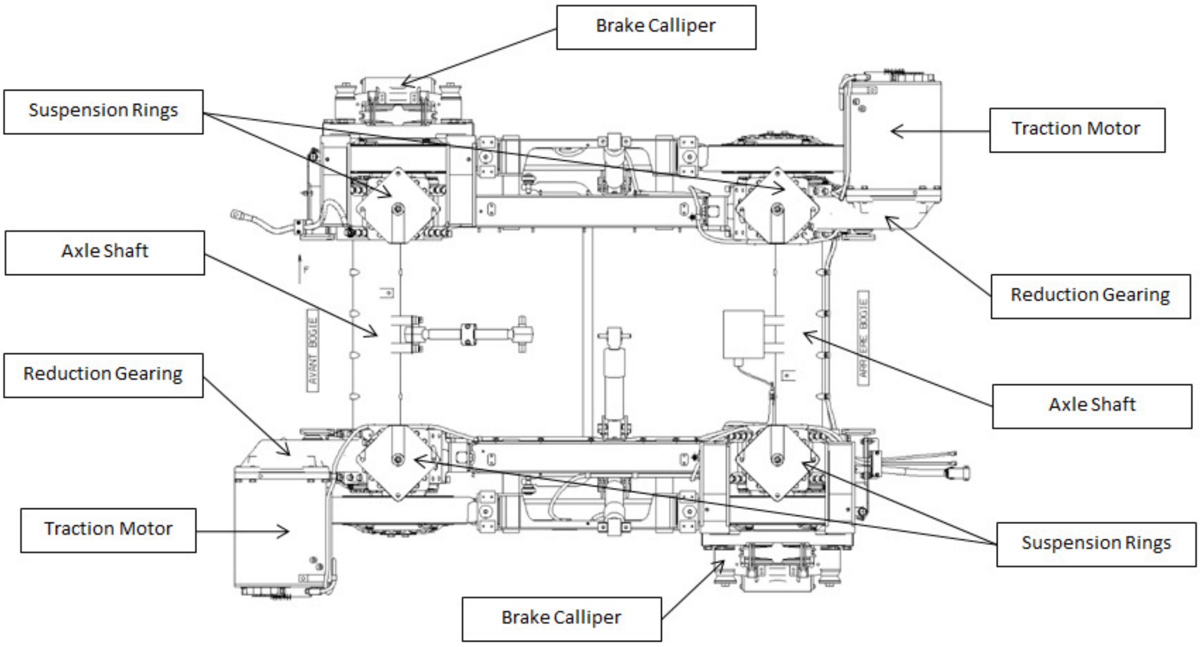


Figure 32: Schematic of Luas Arpeggeo Motor Bogie [93]

In total Luas 401 style vehicles have six traction motors providing traction power for the tram. The LHB bogie traction motors are 140 kW, and the Arpeggeo bogie motors are 120 kW. The total motor power of Luas 401 style vehicles is 800 kW.

Luas 402 style vehicles also have 3 motor bogies all of which are Arpeggeo low floor bogies. Each of the traction motors on the 402 trams has a power rating of 120 kW. The total motor power of Luas 402 style vehicles is 720 kW. All traction motors fitted to Luas vehicles use AC motors. These motors are significantly more efficient than DC motors requiring less voltage. The traction motors on Luas vehicles require a three phase AC supply. As Luas operates in an urban location the OCS is supplied 750 V DC. The DC supplied by the OCS must be inverted to the required AC voltage for the traction motors. This is achieved by the traction bogie control unit (TBCU) which regulates the supply of power to the bogies. The DC current conducted from the OCS through the pantograph passes through what is known as an Onix inverter unit. There is one

Onix inverter unit per motor bogie on each Luas vehicle. The Onix unit consists of a resistor and capacitor, wired in series with a rheostat braking chopper and a triphase inverter which achieves the desired three phase AC current required for the traction motors. The power requirements of the traction motors are approximately 500W during normal operating conditions, the maximum current drawn by these motors can be in the region of 1500A under full load. Figure 33 illustrates the Onix system.

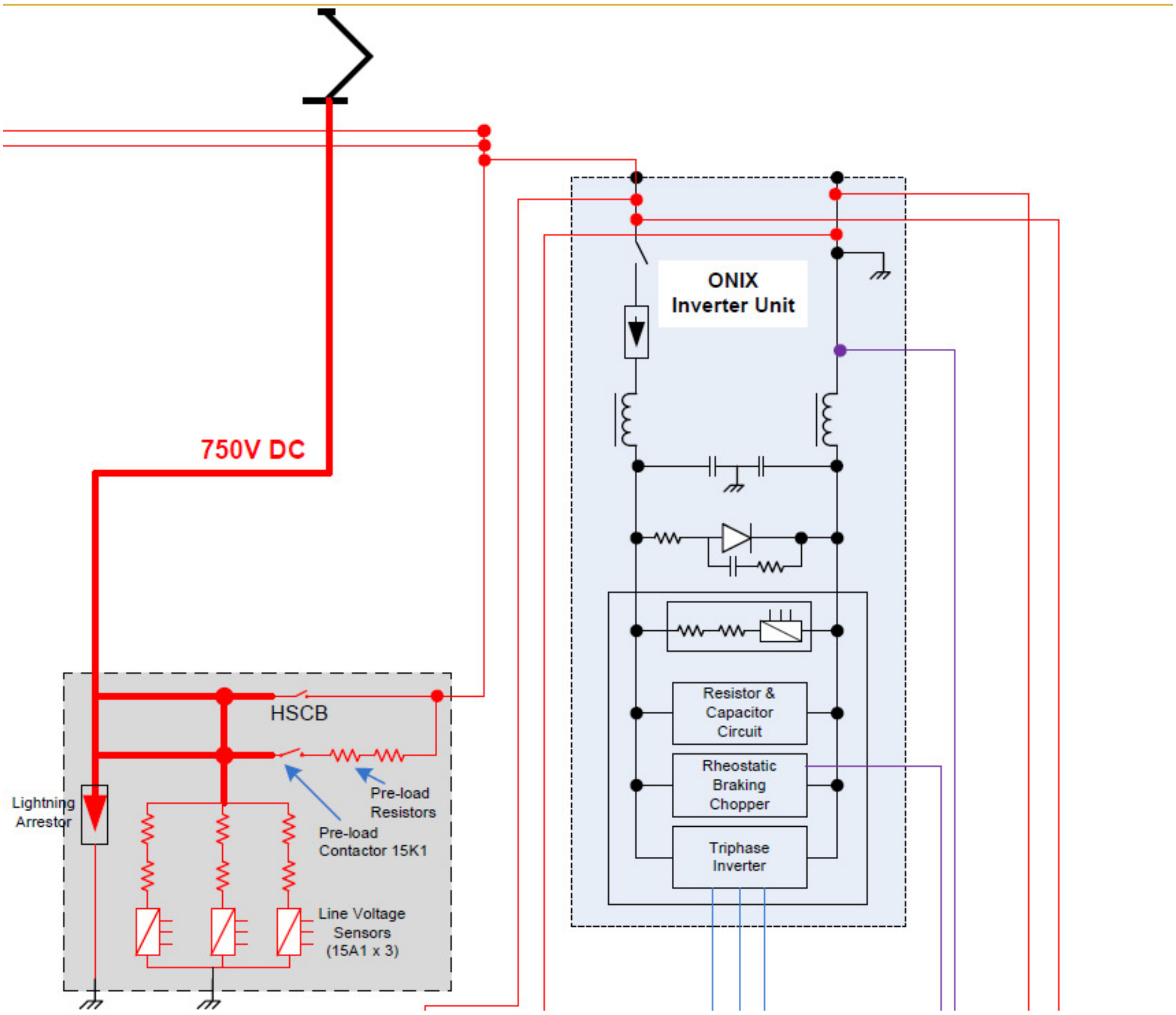
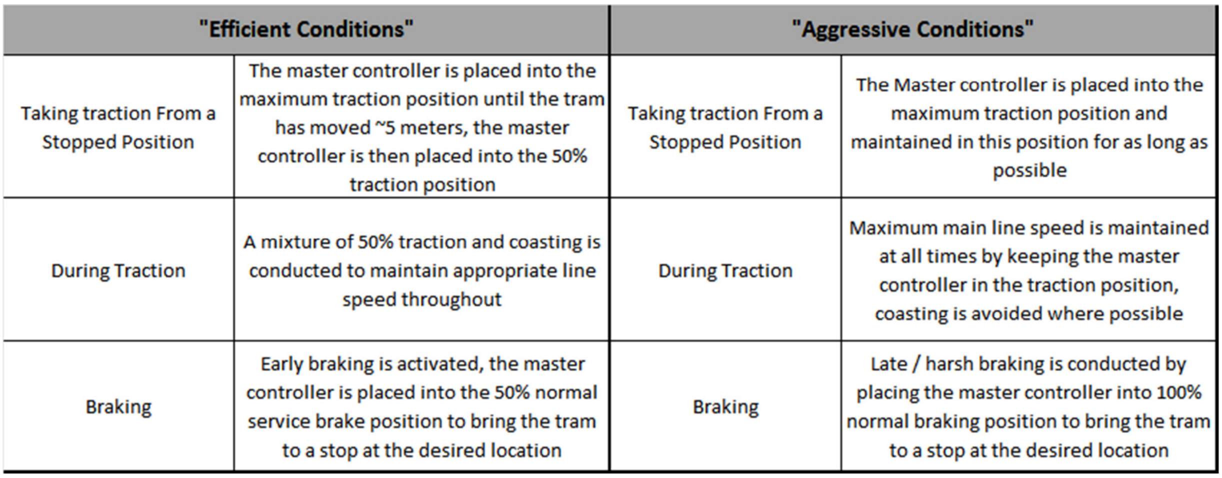


Figure 33: Wiring Schematic of Luas Onix System [92]

Driving styles, passenger loads, operational headways and climatic conditions have a significant impact on the energy consumed by the traction motors on each vehicle. In order to quantify and analyse the consumption of Luas traction motors a series of tests were conducted throughout this research. Testing was performed on the Luas Red Line. The reason for testing on the Red Line was that the energy metering system (Powersoft) had been installed on vehicle number 3010 on the Red Line as detailed in Chapter 3. Using this metering system both live and historic energy consumption data was obtained. The Red line also offered easy access to all Luas IT systems used during these tests within the central control room. These systems include automatic vehicle location system, PS Scada and the vehicle tachometers. Tram drivers were also readily available on the Red Line. Although Luas Red and Green line vehicles differ slightly in terms of motor bogie and traction motor design, the energy consumption differences of both are minimal according to the manufacturers Alstom. The first traction motor energy consumption test was performed on 05/04/2012. The purpose of this test was to establish the differences in the energy consumption of the traction motors based on two pre-determined different driving conditions. The pre-determined driving conditions were established after speaking with one of Luas most experienced drivers. The parameters of these conditions defined as “efficient conditions” and “aggressive conditions” are detailed in Table 6. To ensure constancy between the different tests conducted throughout this research the same driver was used in each case. This driver had thirty years’ experience driving rail vehicles, of which ten years including driving Luas trams.

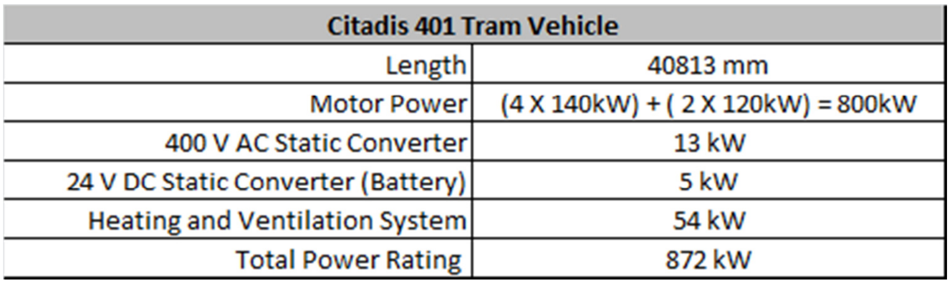
Table 6: Parameters of Luas Tram Testing



"Efficient Conditions"		"Aggressive Conditions"	
Taking traction From a Stopped Position	The master controller is placed into the maximum traction position until the tram has moved ~5 meters, the master controller is then placed into the 50% traction position	Taking traction From a Stopped Position	The Master controller is placed into the maximum traction position and maintained in this position for as long as possible
During Traction	A mixture of 50% traction and coasting is conducted to maintain appropriate line speed throughout	During Traction	Maximum main line speed is maintained at all times by keeping the master controller in the traction position, coasting is avoided where possible
Braking	Early braking is activated, the master controller is placed into the 50% normal service brake position to bring the tram to a stop at the desired location	Braking	Late / harsh braking is conducted by placing the master controller into 100% normal braking position to bring the tram to a stop at the desired location

Testing took place during engineering hours which are between 02:00 and 04:30. Engineering hours are those in which no passenger service is operated on the main line. Testing during these periods allowed for an unobstructed track so that testing could be completed safely without incident. Before testing took place a method statement was produced detailing the test parameters and a permit to complete the tests was granted by Transdev. The test tracks was a full loop of the Red Line, in-bound from the Tallaght stop the Point stop and out-bound from the Point stop to the Tallaght stop. In total the test track was 32.4 km and took approximately 120 minutes to complete. The first test began at the Tallaght stop where the tram (No: 3010) was driven in a pre-determined “efficient conditions”. This incorporated using moderate traction from a stationary position, through coasting until the desired line speed was obtained. Moderate braking was also applied, with the tram speed being reduced over an extensive period before a traffic signal, curved track section or Luas stop. To mirror the parameters of a tram operating in normal passenger service, the test tram obeyed all normal in-service speed limits, resting at each stop and opening all passenger doors at each platform. On the same night a second test was conducted. During this test, the tram was driven in a pre-determined “aggressive conditions”. This incorporated applying full traction from a stationary position to achieve the maximum speed in the shortest time and maintaining maximum line speed throughout. Excessive braking techniques were also applied to stop the vehicle at traffic signals and Luas stops. As with the previous test and to maintain the parameters of a tram operating in normal passenger service, the test tram obeyed all normal in-service speed limits, resting at each station and opening all passenger doors at each platform. Once both tests were complete the tram was returned to the depot. The Tacho from the tram was downloaded, which provided data such as tram speed, acceleration and braking positions for both tests. An AVLS report was exported from the main AVLS server which provided information on the location of the vehicle throughout the system relative to the specific time periods of each test. The energy consumed during both tests was metered and recorded by the Powersoft tram metering system. This data was extracted from the Powersoft server once the test was complete. The desired results of this test were to establish the differences in the energy consumption of the tram traction motors based on the two pre-determined driving conditions. Table 7 details the power rating of Luas 401 vehicles used during these tests.

Table 7: Luas Power Rating



Citadis 401 Tram Vehicle	
Length	40813 mm
Motor Power	(4 X 140kW) + (2 X 120kW) = 800kW
400 V AC Static Converter	13 kW
24 V DC Static Converter (Battery)	5 kW
Heating and Ventilation System	54 kW
Total Power Rating	872 kW

Figures 34 and 35 display the speed profile for the test track in both the in-bound and out-bound directions. The speed profile for both tests was comparable as normal line speed conditions were adhered to at all times. In the “aggressive conditions” test the maximum speed was achieved in a shorter time period compared to the “efficient conditions” test due to the increased acceleration from a stop position. The maximum permitted speed of the Luas light rail system is 70 km/h. This maximum speed is only achieved on segregated sections of track outside the city centre locations. On shared section of track, particularly in the city centre the maximum speed is 30 km/h.

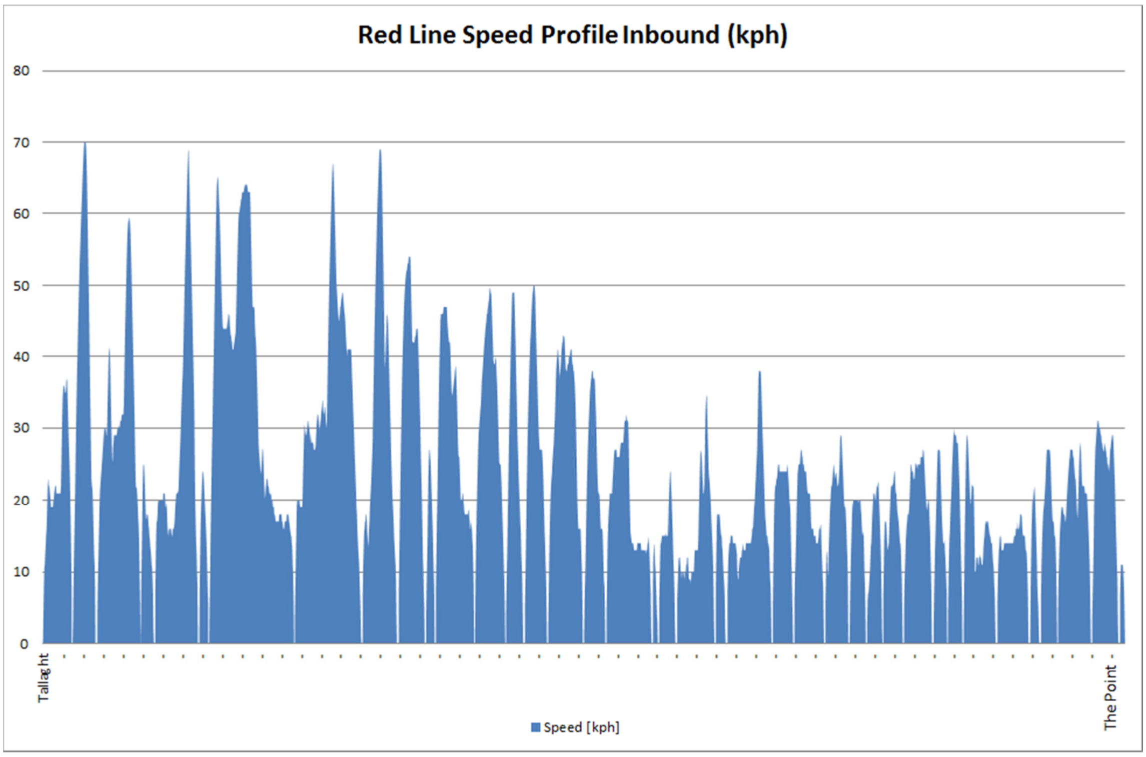


Figure 34: Test Speed Profile In-Bound

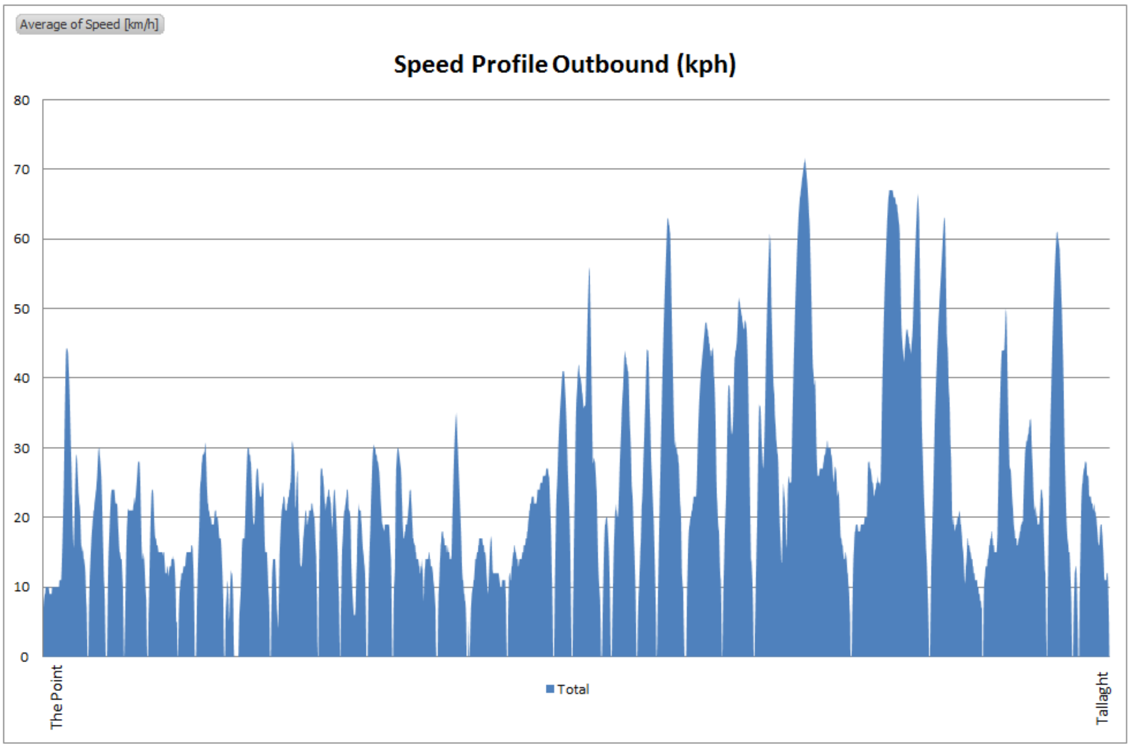


Figure 35: Test Speed Profile Out-Bound

Figure 37 illustrates the position of the master controller relevant to the speed of the tram on the in-bound journey. Traction is represented by blue, coasting is represented by red and braking is represented by green. As the gradient profile of the Red Line track is 104 meters over 19.5 km in the out-bound direction, increased tractive effort is required on the out-bound journey. In the opposite instance, increased braking is required on the in-bound journey due to downhill gradients prior to Luas stops or road junctions. This theory is confirmed in the proceeding Figures 36 and 37.

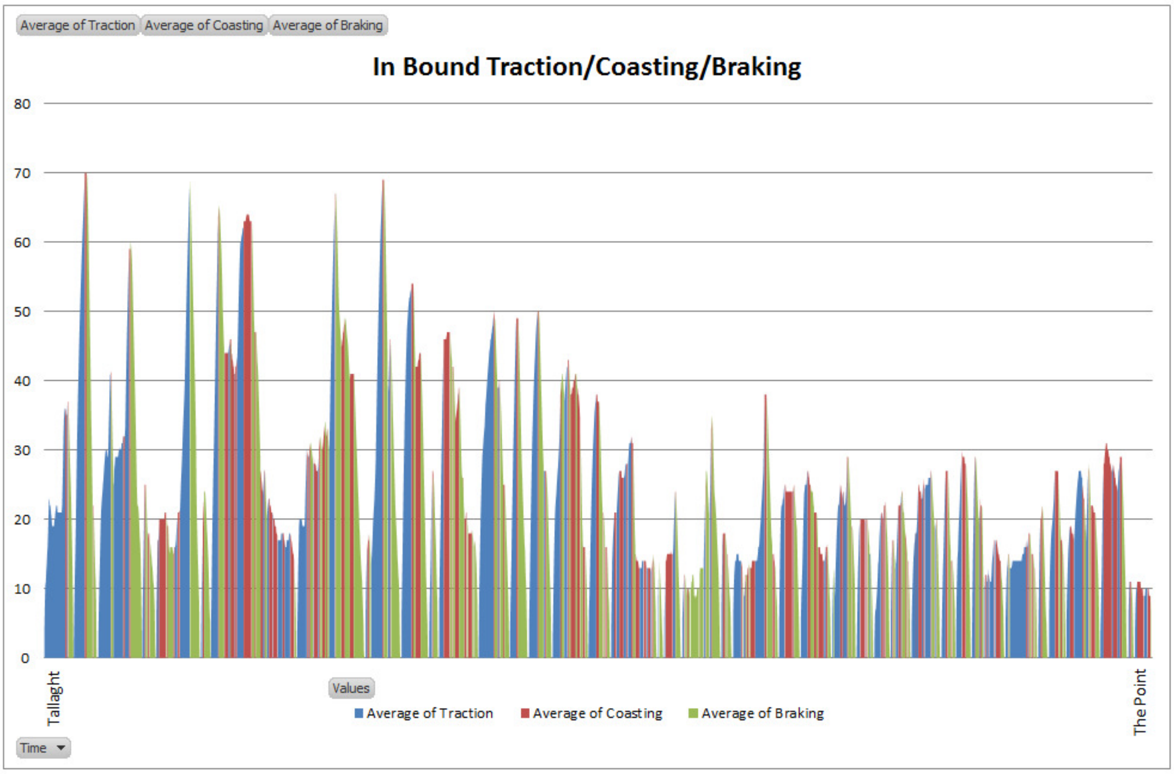


Figure 36: In-bound Test Traction, Coasting, Braking Profile

Figure 37 illustrates the master controller position for the out-bound journey. Traction is represented by blue, coasting is represented by red and braking is represented by green in this figure also. Increased traction can be seen in Figure 37 on the out-bound journey due to the gradient profile of the track.

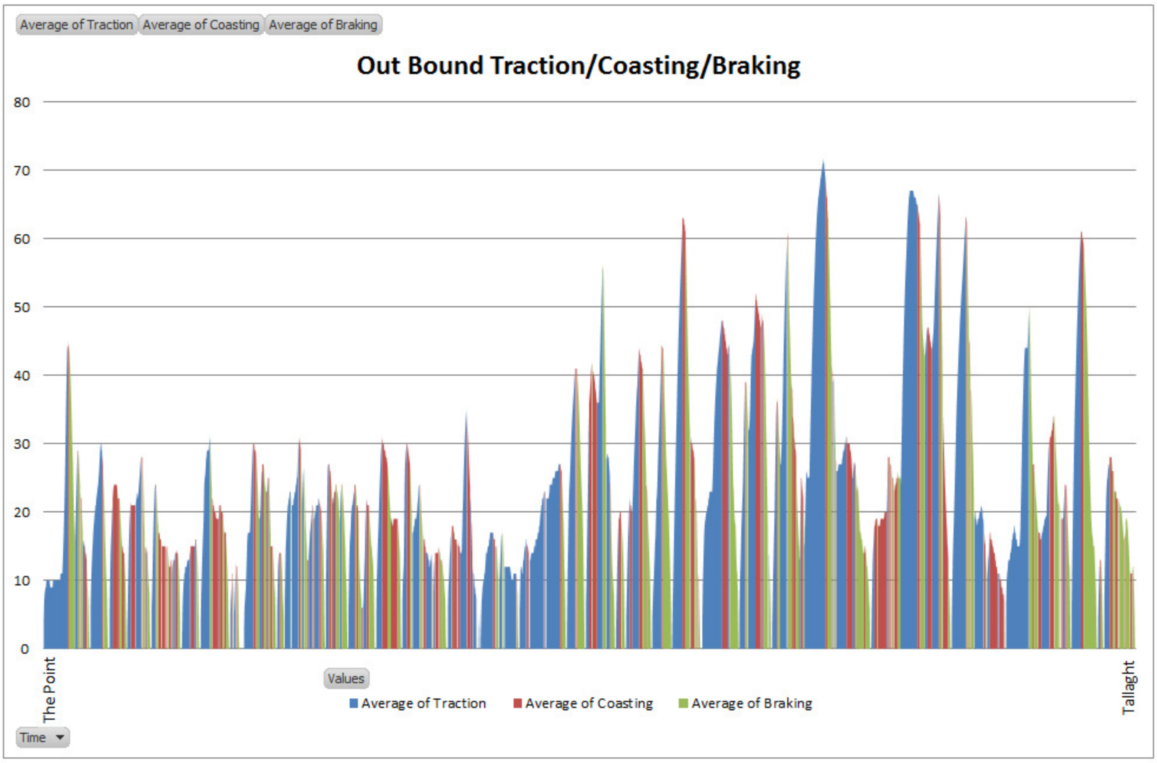


Figure 37: Out-bound Test Traction, Coasting, Braking Profile

Figure 38 illustrates the power consumed from the traction motors for each test. This graph indicates the increased power consumed during the "aggressive conditions" test when compared to results of the "efficient conditions" test.

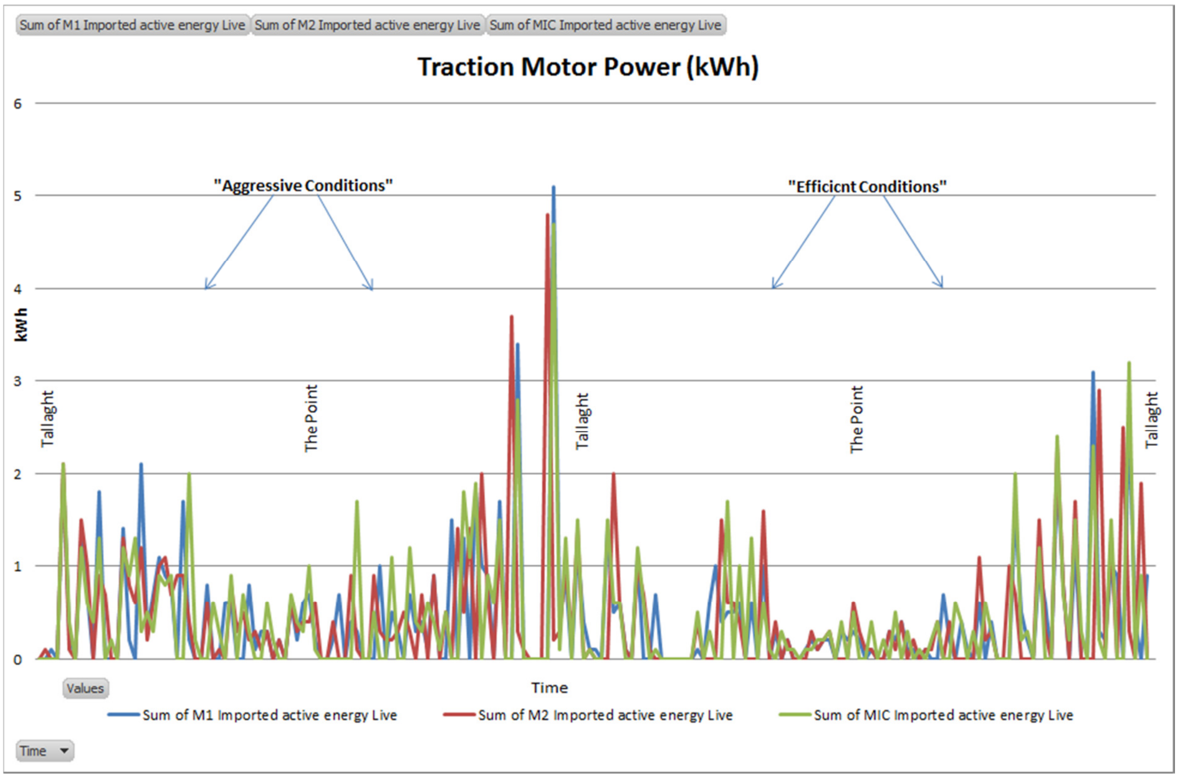
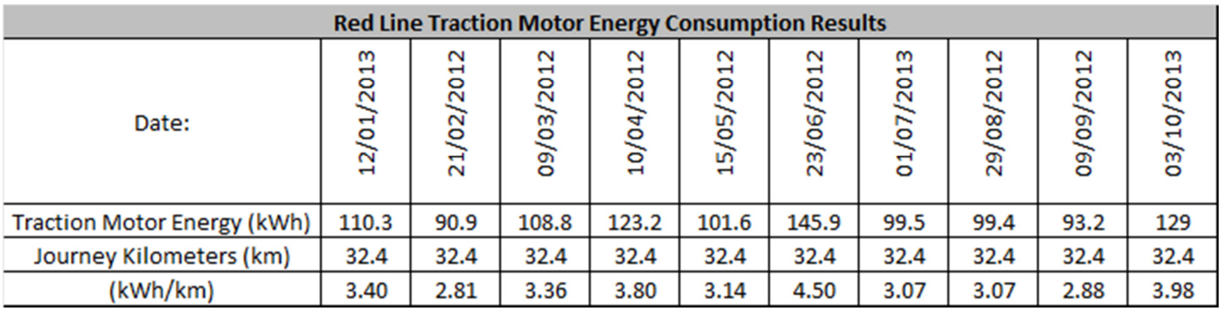


Figure 38: Traction Motor Energy

The outcomes of these tests proved that particular driving conditions have a direct impact on the energy consumed by the traction motors for the corresponding sections of track. Test one verifies that driving in the pre-defined “efficient conditions” has a significant positive influence on the energy consumed by the motors. In the opposite instance, test two proves that if a tram is driven in an “aggressive conditions” the energy consumption increases notably. In summary, the total consumption of the traction motors during the “aggressive conditions” test was 140.9 kWh or 4.34 kWh/km. For the “efficient conditions” test the consumption was recorded to be 100.1 kWh or 3.08 kWh/km. This represents a 71% increases in traction motor power between the two tests. To validate these results the energy consumption of the traction motors during normal passenger service was monitored throughout the research period. Each of the trams monitored were driven by different drivers in a range of conditions. Conditions such as passenger numbers at peak and off-peak times, operating timetables and headways and climatic conditions will all have a contributing impact on energy consumption. Table 8 details the energy consumption of the traction motors for a number of random in-service trams operating on the Luas Red Line.

Table 8: Traction Motor Energy Results



Red Line Traction Motor Energy Consumption Results										
Date:	12/01/2013	21/02/2012	09/03/2012	10/04/2012	15/05/2012	23/06/2012	01/07/2013	29/08/2012	09/09/2012	03/10/2013
Traction Motor Energy (kWh)	110.3	90.9	108.8	123.2	101.6	145.9	99.5	99.4	93.2	129
Journey Kilometers (km)	32.4	32.4	32.4	32.4	32.4	32.4	32.4	32.4	32.4	32.4
(kWh/km)	3.40	2.81	3.36	3.80	3.14	4.50	3.07	3.07	2.88	3.98

The values detailed in Table 8 were obtained at random across 2012 and 2013. All trips were performed on tram number 3010 by different Luas drivers, all trips were a full loop of the Red Line from Tallaght to the Point and back. The results also cover a cross section of weekday and weekend peak and off-peak operations. The length of time taken to complete the trips of the above listed results were analysed to ensure each trip was conducted between 50 and 70 minutes. This is the normal in service time consumed for trips from Tallaght to the Point and back. A review of the TED was also conduced to ensure no reports of tram defects, operational delays, safety or vandalism events were recorded which resulted in these services being obstructed. Such events, although a feature of an open LRT system, may result in increased energy being consumed by the tram. The weather conditions were also considered when selecting these results. Rain, fog or snow can have an impact on Luas operations. Where track adhesion is low trams may suffer wheel slip on taking traction or during braking. In dense fog situations where visibility is poor speed restrictions may be imposed, similarly where snow is building on the ground speed restrictions may be put in place by the central control room. These instances would be reported in TED should they have occurred. The results indicate a variable value from a minimum of 2.81 kWh/km to a maximum of 4.56 kWh/km. This variant in energy consumption includes driving styles and operating conditions. It should be noted that these tests omit power generated through braking, the heating and ventilation system energy consumption and also the static converter energy consumption, all of which are detailed later in this Chapter.

4.1.2 Regenerative Braking

One component of the braking system on the motor bogies of Luas vehicles is that of regenerative braking. The current generated from the regenerative system can be harvested by the Luas system as described in sections 2.4 of Chapter Two. If the parameters do not exist for the system to harvest the current generated from braking, it will be dissipated as heat through three resistor rheostat banks located on the top of each vehicle. If the current is dissipated as heat, a significant amount of energy may potentially be lost [94]. Harvesting regenerative braking energy will depend on a number of factors including the number of vehicles in operation, the time of operation (peak or off-peak), the capabilities of OCS in the electrical section of track where the vehicle is braking and the profile of the track at that location. To analyse the potential capabilities of the regenerative braking system of Luas vehicles a range of tests were conducted. Testing again took place on the Red Line as the relevant systems were available. As with the previous traction motor energy consumption tests, the two pre-determined “efficient” and “aggressive” driving conditions were employed. The same tram and test track was also used. The aim of these tests were to establish how much power was being regenerated during braking, and of this power, what percentage was harvested by the system.

From Figure 39 it is apparent that during the “aggressive conditions” test significantly more power was generated under braking compared to the “efficient conditions” test. This was due to the aggressive braking techniques adopted during this test.

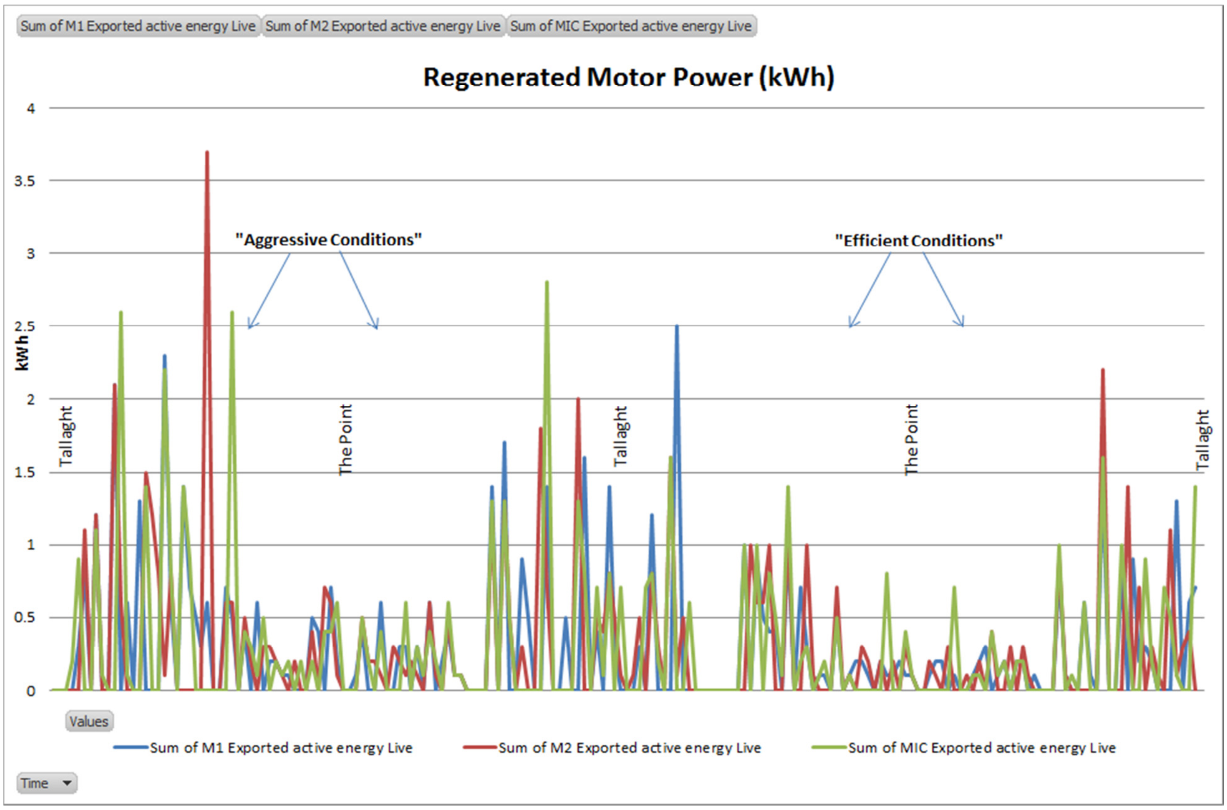


Figure 39: Regenerated Energy

Of this energy generated under braking, Figure 40 represents the amount of regenerated energy that was dissipated as heat through the rheostats resistor banks for the same period. This power was lost by the system as it could not be harvested at that instance.

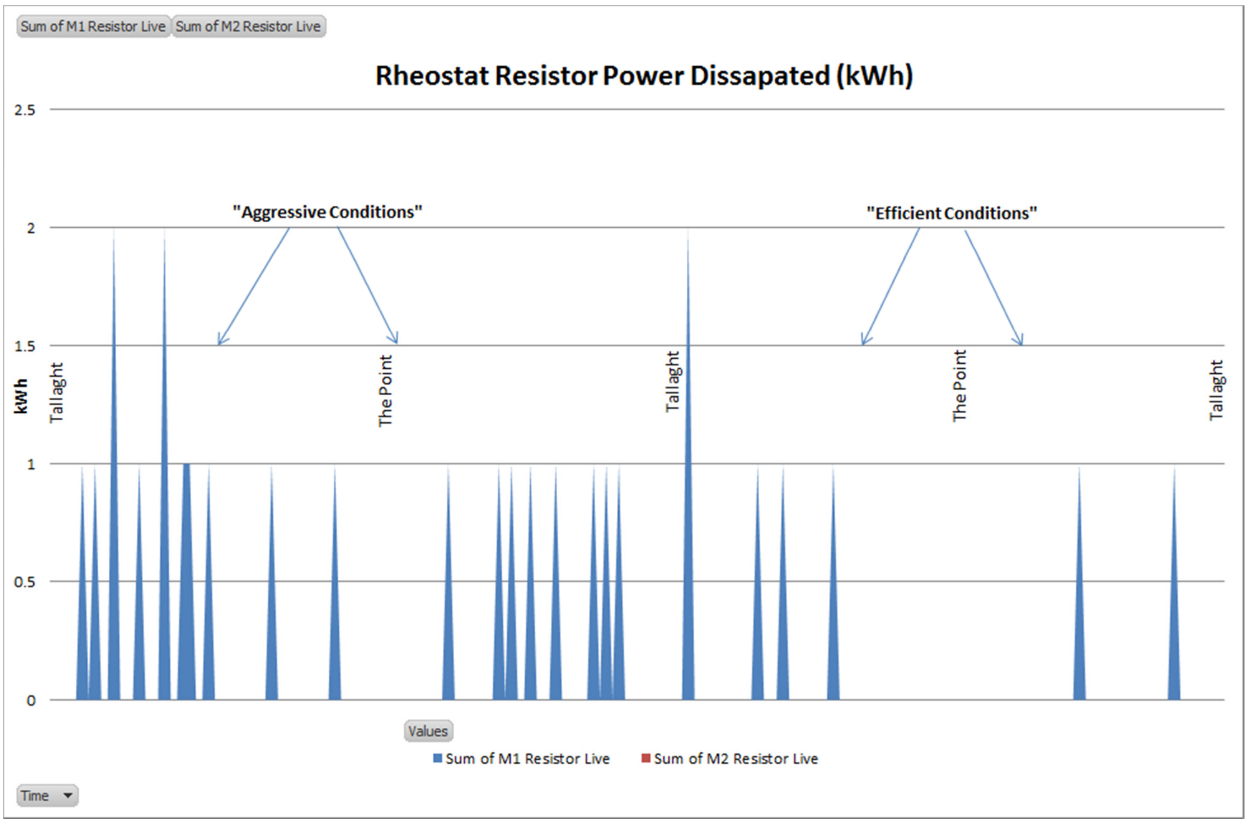
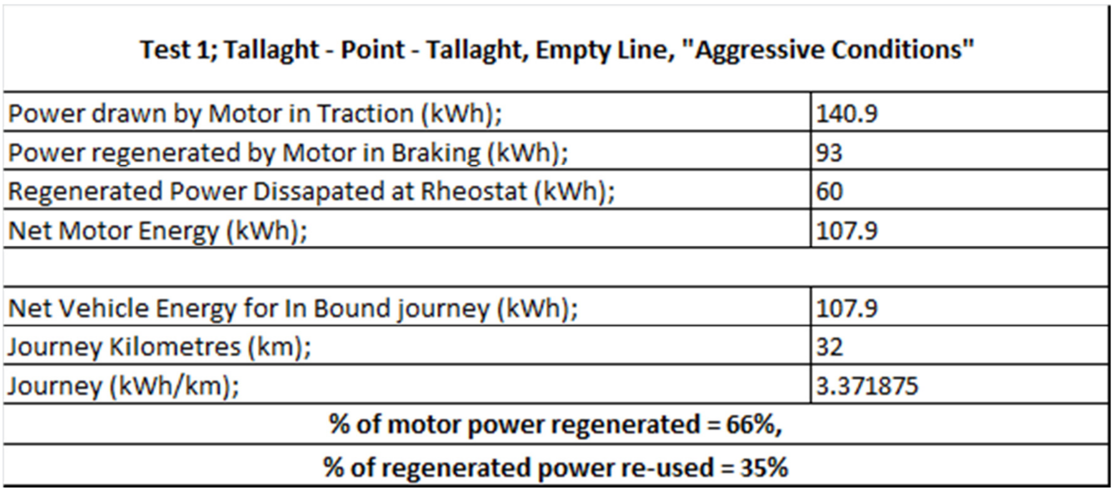


Figure 40: Regenerated Energy Dissipated at Rheostat

During the “aggressive conditions” test, the tram was generating significant amounts of energy under braking, however this energy was not being capitalised by the system when compared with the “efficient conditions” test. Table 9 represents the results of the “accelerated conditions” test. Here it was found that 66% of traction power was being regenerated under braking with 35% of this power being re-used by the system.

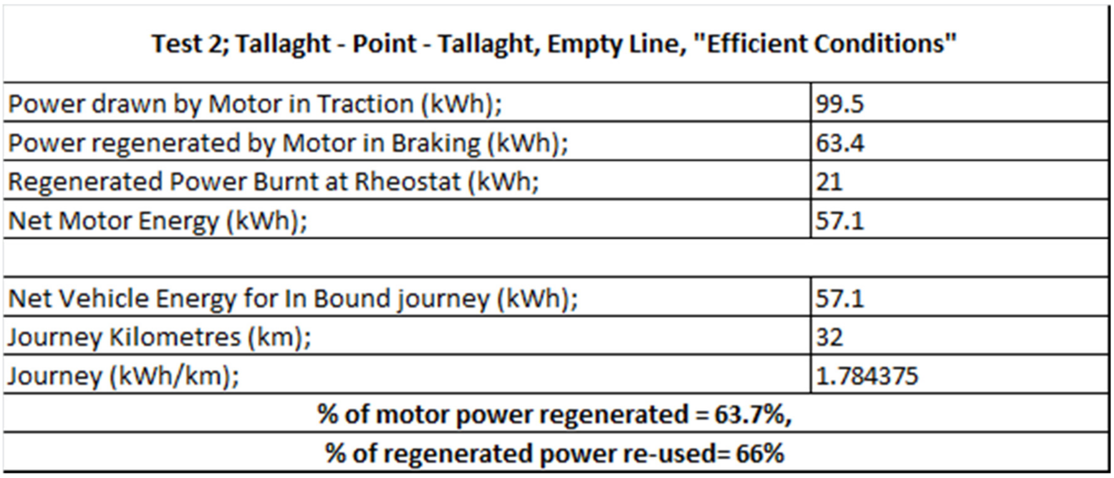
Table 9: Aggressive Conditions Test Results



Test 1; Tallaght - Point - Tallaght, Empty Line, "Aggressive Conditions"	
Power drawn by Motor in Traction (kWh);	140.9
Power regenerated by Motor in Braking (kWh);	93
Regenerated Power Dissapated at Rheostat (kWh);	60
Net Motor Energy (kWh);	107.9
Net Vehicle Energy for In Bound journey (kWh);	107.9
Journey Kilometres (km);	32
Journey (kWh/km);	3.371875
% of motor power regenerated = 66%,	
% of regenerated power re-used = 35%	

Table 10 represents the results of the “efficient conditions” test. Here 63.8% of traction power was regenerated during braking, with 66% of this power being re-used by the system.

Table 10: Efficient Conditions Test Results



Test 2; Tallaght - Point - Tallaght, Empty Line, "Efficient Conditions"	
Power drawn by Motor in Traction (kWh);	99.5
Power regenerated by Motor in Braking (kWh);	63.4
Regenerated Power Burnt at Rheostat (kWh;	21
Net Motor Energy (kWh);	57.1
Net Vehicle Energy for In Bound journey (kWh);	57.1
Journey Kilometres (km);	32
Journey (kWh/km);	1.784375
% of motor power regenerated = 63.7%,	
% of regenerated power re-used= 66%	

From these results it is clear that during “aggressive conditions” test, the system is not capable of harvesting the regenerated energy as the instantaneous current is too great. As a result the energy is dissipated as heat through the rheostats and is effectively lost. During normal operating conditions 66% of the regenerated power is re-used by the system. These figures compares well with similar light rail systems around Europe.

4.1.3 Passenger Heating and Ventilation System

The Luas heating and ventilation systems are the only other components fitted to vehicles which draw power directly from the OCS at 750 DC. Luas Citadis 401 and 402 style trams have three passenger heating and ventilation systems installed [95]. The units are located on the roof sections of SC1, CC2 and SC2 cars as shown in Figure 41.

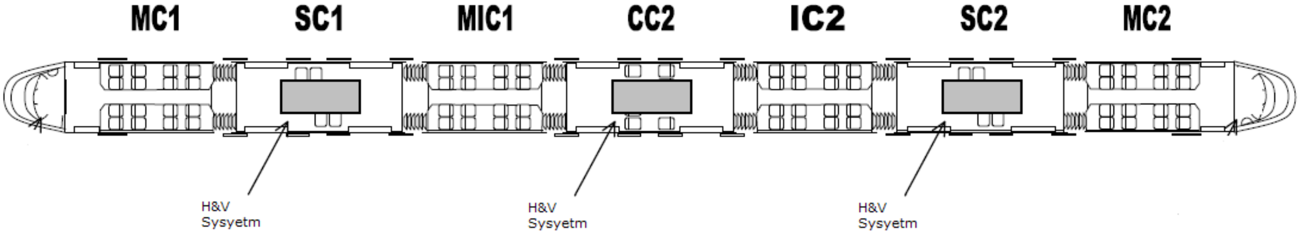


Figure 41: Location of Heating and Ventilation units [95]

The Luas heating and ventilation system consist of a self contained unit (2036 mm x 1195 mm) which houses a fresh air inlet, a recirculated air inlet (controled by a mechanical flap), a resistor heater element, a ventilation fan, temperature sensing probes and a control unit. The electric heaters consist of three layers of electrical elements mounted on a stainless steel base, with a flow area of 852 mm x 155 mm (1.32 m²) shown in Figure 42. These heaters have a rated power of 18 kW each. Power is supplied by way of 750 V DC from the overhead centenary supply as illustrated in Figure 43.

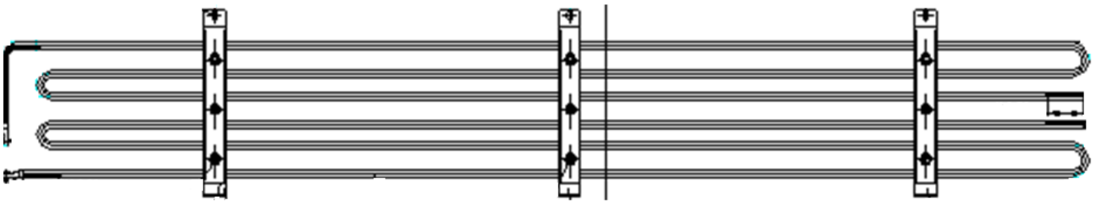


Figure 42: Resistor Heating Elements [95]

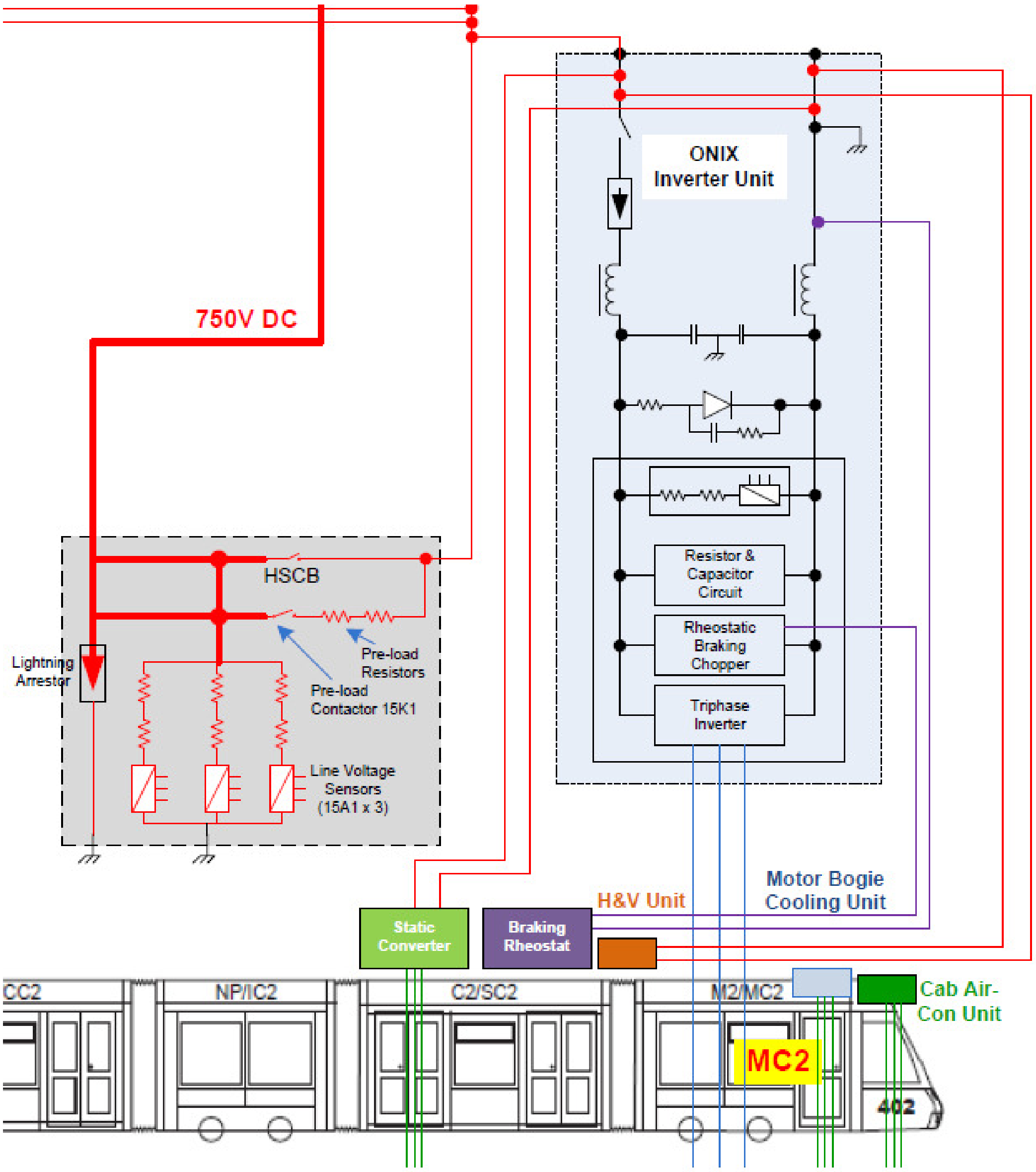


Figure 43: Heating and Ventilation Unit Wiring Schematic [92]

Ventilation is provided by a fan located within the base of each heating and ventilation units. The fan is powered by a motor which is supplied from the 400 V AC static converter. The maximum power output is 510 W, at a rated speed 1400 rpm allowing for a maximum airflow of 3600 m³/h. Thermostatic temperature probes located at the base of the fan measure the temperature of the air being recirculated from the passenger saloon. A second thermostatic temperature probe is located at the fresh air inlet which measures the temperature of the external air. There is also a third probe located adjacent to the heater elements functioning as a backup should the elements overheat. Figure 44 shows the heating and ventilation unit and various components.

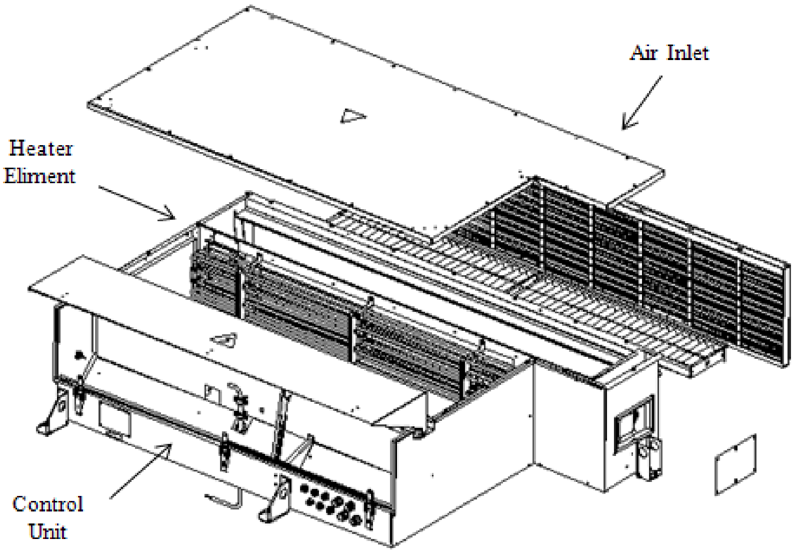


Figure 44: Heating and Ventilation Unit Schematic [95]

Figure 45 shows the heating and ventilation unit ventilation fan.

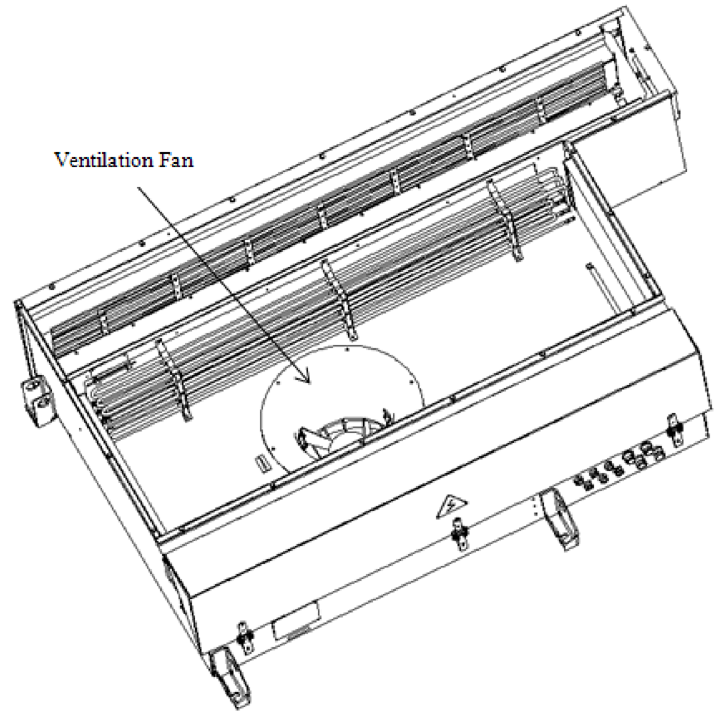


Figure 45: Heating and Ventilation Fan Schematic [95]

Each of the heating and ventilation systems are controlled by a self-contained control unit located within the heating and ventilation housing. Figure 46 details the electrical schematic of the systems.

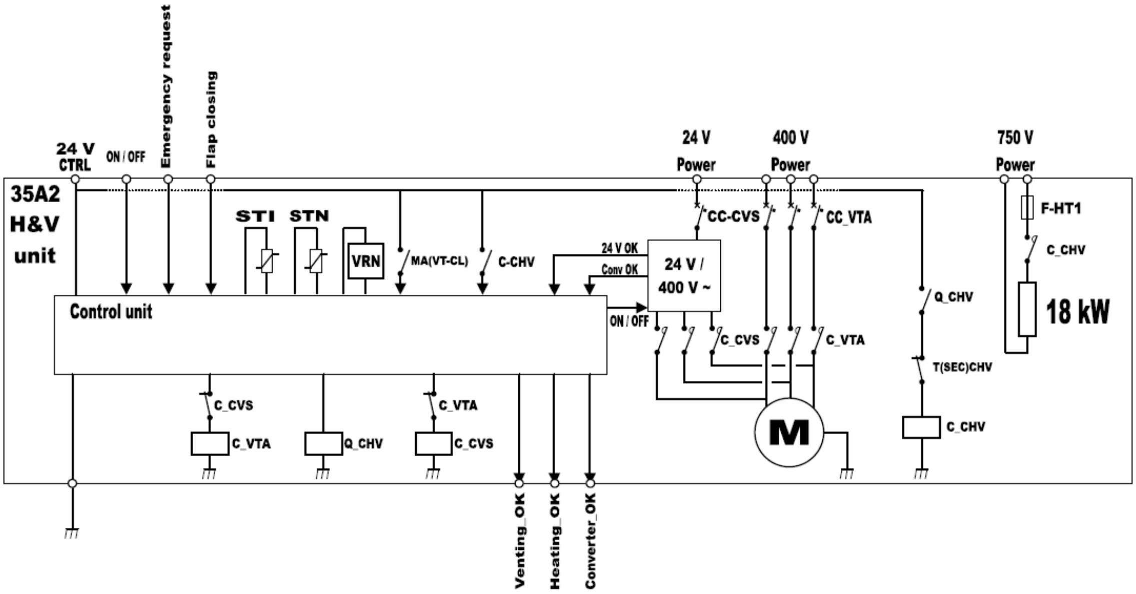


Figure 46: Heating and Ventilation Electrical Control Diagram [95]

With no air cooling option the system is limited in its capabilities, however the climate of operation in Ireland does not on average require the need for cooling. In all eventualities the system endeavors to achieve a set interior temperature. This temperature is determined by a set point formula which is influenced by the exterior air temperature. The set point formula is 20 ºC + 0.25 x (STN – 17 ºC) where STN is the temperature of the fresh air at the inlet.

Figure 47 shows the set point profile.

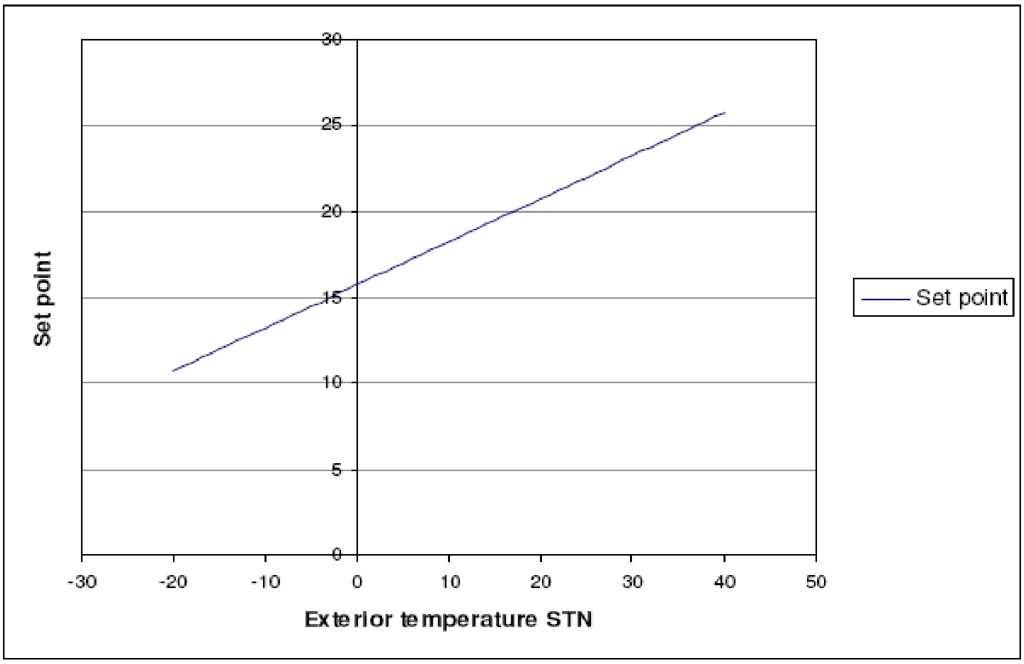


Figure 47: Heating and Ventilation Set Point Profile [95]

There are three functional setting to which the heating and ventilation system will operate to achieve the set point temperature within the passenger saloon.

i). When STI < set point – 3 °C

(Where STI is the temperature of the air within the passenger saloon)

If the above conditions are met the temperature of the air in the passenger saloon is at least 3ºC below the temperature of the external air. In this case the heating system is working at a maximum level. The heating resistor is commanded at 100 % and the air fresh inlet is closed resulting in the air from the passenger saloon being recirculated and heated before being supplied back into the saloon.

ii). When the set point – 3 ºC < STI < set point + 3 ºC

(Where STI is the temperature of the air within the passenger saloon)

In this scenario the interior temperature will be +/- 2 °C of the set point. The control system continuously monitors the temperature of the air in the passenger saloon. A proportional integral derivative (PID) controller calculates if the temperature of the air is greater or less than the set point. In order to bring the temperature of the air within the saloon back to the set point temperature, the air inlet flap is adjusted by a flexible damper. By adjusting the air inlet flap the ratio of external air to recirculated air supplied through the system can be changed.

iii). When (set point + 3 ºC < STI) AND (STN > 17 ºC)

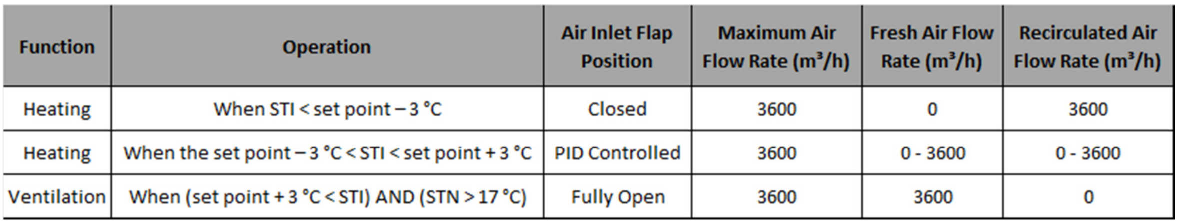
(Where STI is the temperature of the air within the passenger saloon)

(Where STN is the temperature of the external air)

In the above scenario the temperature of the air within the saloon is at least 3ºC above the set point, and the external temperature is greater than 17 ºC. In this case the heating resistor is switched off and as the system has no air cooling feature the fresh air inlet is fully open to a maximum allowing fresh air to circulate throughout the saloon.

Table 11 details the operation of the system including the position of the air inlet flap and the ratio of fresh air to recirculated air [95].

Table 11: Heating and Ventilation Operation

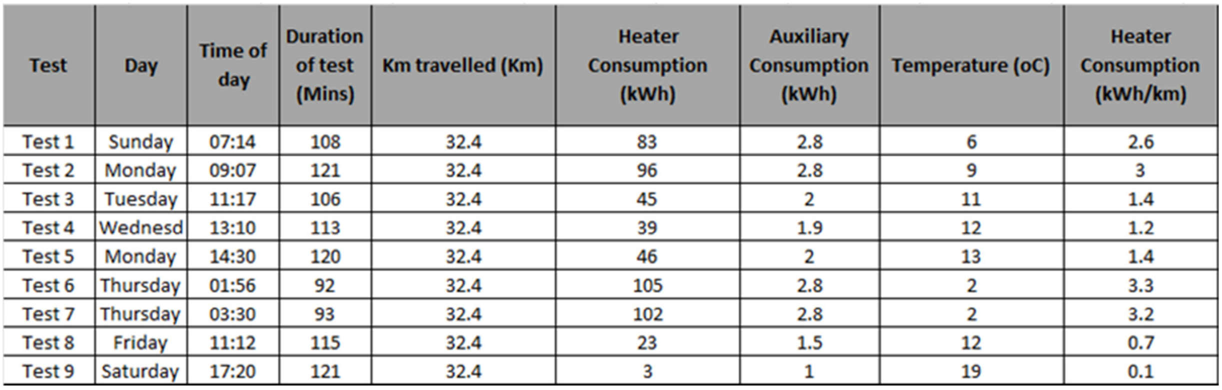


Function	Operation	Air Inlet Flap Position	Maximum Air Flow Rate (m^3/h)	Fresh Air Flow Rate (m^3/h)	Recirculated Air Flow Rate (m^3/h)
Heating	When STI < set point – 3 °C	Closed	3600	0	3600
Heating	When the set point – 3 °C < STI < set point + 3 °C	PID Controlled	3600	0 - 3600	0 - 3600
Ventilation	When (set point + 3 °C < STI) AND (STN > 17 °C)	Fully Open	3600	3600	0

The heating and ventilation system is set up to automatically start once the vehicle is first prepared (switched on). The system will remain on (temperature depending) until such time as the vehicle is de-prepped (switched off). The heated or fresh air supplied by the system is fed into a main duct located on the roof of the interior passenger compartment. Two lateral vents of 1600 mm located on either side of the main roof duct in cars M1, CC and M2 supply the air to the main passenger compartment at an average rate of 3600 m^3/h. According to EN 14750 [96], the required fresh air in a transport mode such as Luas is 12 m^3/h/passenger. This is to ensure safe levels of CO_2 which should be constantly below 1000 ppm. Studies by Neu [57] demonstrate Luas has an air change rate (ACH) of between 134.33 m^3/h/pass, at minimum passenger occupancy of approximately 43 ppm^2 and an ACH of 27.63 m^3/h/pass at a maximum passenger occupancy of 236 ppm^2. This is provided by the heating and ventilation system (51%), through natural ventilation (35%) (doors opening) and through infiltration (14%). These results achieve the minimum standard, and as a result the CO_2 levels within Luas passenger's compartments are lower than the allowances of 1000 ppm. Luas has an average ACH of 80.98 m^3/h/pass, which is six times the required by European Standard [96].

Light rail vehicle heating and ventilation systems consume significant amounts of energy especially during winter months. In order to establish the efficiency of Luas heating and ventilation and the electrical loads, testing took place throughout a range of operating conditions. A number of tests were performed during 2012 to establish the energy consumption relevant to the external temperature. Testing took place during passenger service operations, when passengers were on-board. Table 12 outlines the results of these tests.

Table 12: Heating and Ventilation Testing Results



Test	Day	Time of day	Duration of test (Mins)	Km travelled (Km)	Heater Consumption (kWh)	Auxiliary Consumption (kWh)	Temperature (oC)	Heater Consumption (kWh/km)
Test 1	Sunday	07:14	108	32.4	83	2.8	6	2.6
Test 2	Monday	09:07	121	32.4	96	2.8	9	3
Test 3	Tuesday	11:17	106	32.4	45	2	11	1.4
Test 4	Wednesd	13:10	113	32.4	39	1.9	12	1.2
Test 5	Monday	14:30	120	32.4	46	2	13	1.4
Test 6	Thursday	01:56	92	32.4	105	2.8	2	3.3
Test 7	Thursday	03:30	93	32.4	102	2.8	2	3.2
Test 8	Friday	11:12	115	32.4	23	1.5	12	0.7
Test 9	Saturday	17:20	121	32.4	3	1	19	0.1

Figure 48 details the heating and ventilation system consumption for a random passenger service operation of the Luas Red Line.

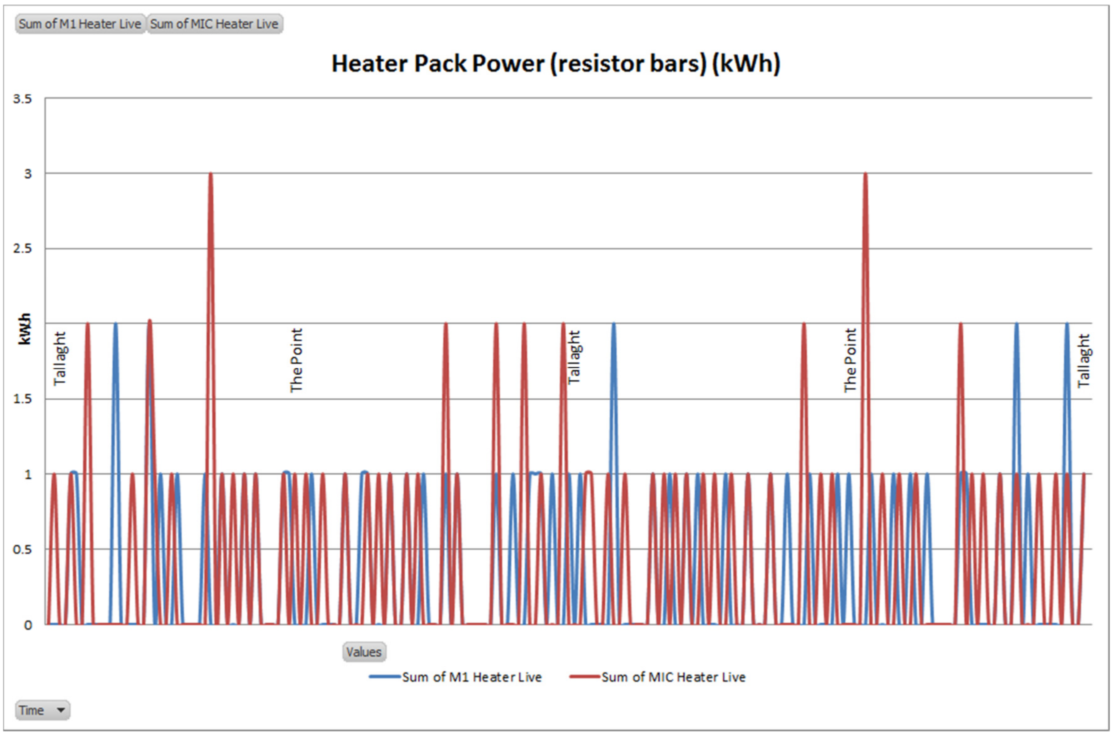


Figure 48: Heater and Ventilation Unit Consumption

From testing it was found that the energy consumption of the heating and ventilation systems on Luas trams was consuming in excess of 60% of total power during winter months. In some cases the consumption of the system was greater than that of the traction motors. It was also found that once the external temperature dropped below 4 ºC, the system is active in heating mode 100% of the time it is activated. This resulted in a consumption value of between 55 to 60 kWh per tram. The design energy consumption for the heating and ventilation systems on Luas vehicles at the original modelling stage was 5% of total traction power per tram. These tests indicate the inefficiencies with the system and the high energy consumption, which is twelve times its design allowance in certain circumstances. A modification to Luas heating and ventilation systems to increase efficiency would result in significant energy savings.

4.1.4 Rolling Stock Systems

The interior lighting of Luas tram vehicles is divided into two parts, the passenger compartment lighting and the drivers cab lighting. Passenger compartment lighting is supplied by florescent tubes fitted in the ceiling of the vehicle. Power is supplied by the static converter through the battery at 24 V DC. Lighting is controlled by the driver from the active driving cab using the saloon lighting push button. The passenger compartment lighting consists of 52 X 36 W fluorescent tubes. If the tram is de-prepped and the lighting switch is de-pressed the battery will supply power to the standby lighting fittings in the saloon. The drivers cab lighting is provided by one 18 W fluorescent tube and can be activated from both driver's cabs using a push button [97].

The passenger compartment lighting has 2 levels:

i). Level 1 = stand-by lighting

ii). Level 2 = stand-by and normal lighting

Level 2 is the normal operating condition for the passenger compartment lighting, while operating in passenger service, as shown in Figure 49.

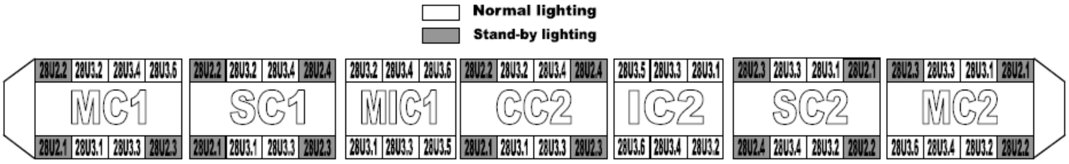


Figure 49: Citadis Internal Lighting Layout [97]

Luas exterior tram lighting is also divided into two parts including front end lighting and side marker lights and indicators.

The lighting modes of Luas vehicles include:

i). Two road type white lights with three positions;
  a) Forward marker lights
  b) Dipped headlight
  c) Full beam headlights
ii). A front white light located on the vehicle's axis above the driver's seat in the cabin.
iii). Two red signals including;
  a) Brake lights
  b) Rearward marker lights
iv). Two red fog lights showing the vehicle when visibility is reduced.
v). Two orange double (hazard and direction indicator lights 21 W and marker lights 5 W on each side.

The exterior light fittings are illustrated in Figures 50 and 51.

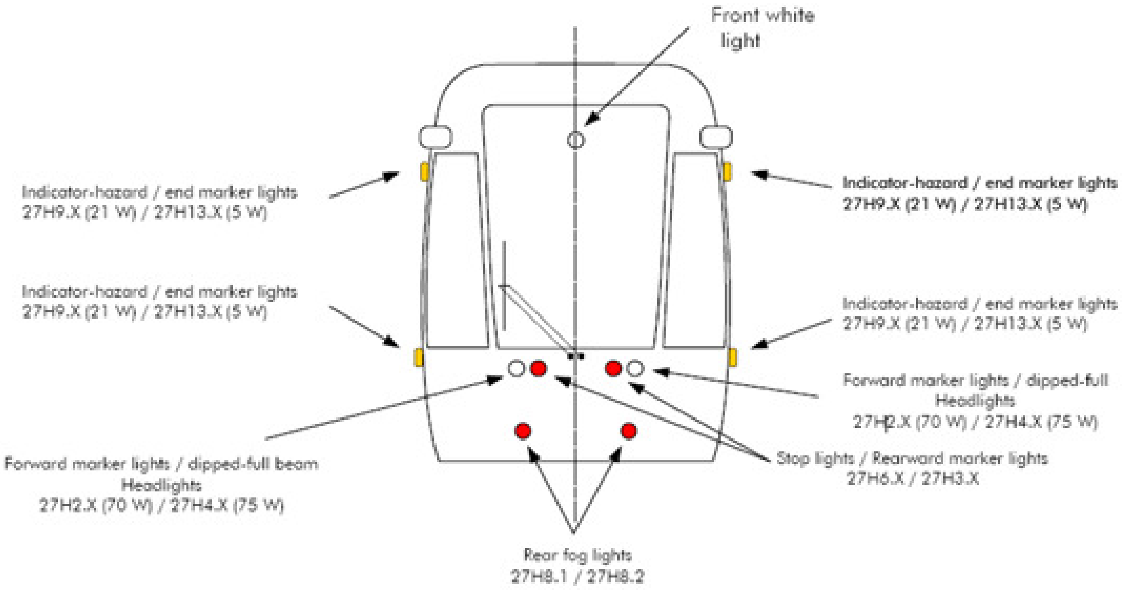


Figure 50: Citadis External Front Lighting Layout [97]

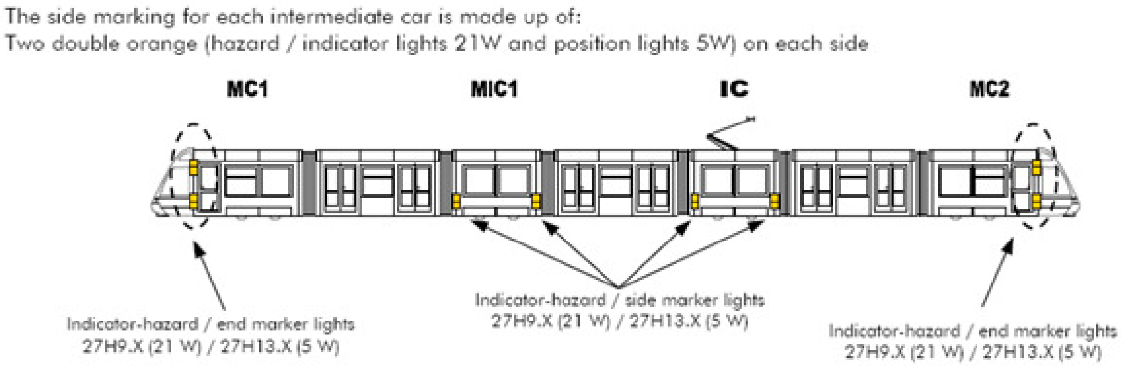


Figure 51: Citadis External Side Lighting Layout [97]

The normal operation of tram exterior lighting is automatic activation of low beam headlights in the active driving cab and rear red marker lights which also act as brake lights. The marker lights located on the side of the vehicle are also automatically activated once the vehicle is prepped. The total exterior lighting amounts to 260 W. If the high beams and indicator lights are activated the power increases to 586 W. Power for the exterior lights is provided by the low voltage 24 V DC static converter, wired through the battery [97].

All the remaining electrical components on Luas vehicles are supplied power by two static converters located on the roof of each vehicle. These components include the drivers cab air conditioning unit, passenger door motors, computer and IT systems such as the AVLS, on-board computer system and the traction bogie control unit. The two static converter (SC) units supply controlled 400 V AC power and 24 V DC power to these systems. The 400 V AC static converter is supplied with 750 V from the OCS via the Onix. This medium voltage DC is then transformed into 400 V, 50 Hz (3 phase with neutral). The maximum consumption of the AC static converter is in the region of 13 kW. The second static converter provides a permanent low voltage 24 V power supply through the main battery to the remaining on-board systems which require a low voltage feed. This unit is in fact powered by the 400 V static converter when the vehicle is prepped. When the vehicle is de-prepped the battery will supply the 24 V DC power [98].

Figure 52 represents the static converter consumption for a random passenger service trip of the Red Line. It can be seen that the consumption does not increase in any considerable amount between each tests, as the tram systems are activated once the tram is prepped, driving styles and other operating conditions do not affect tram systems energy consumption.

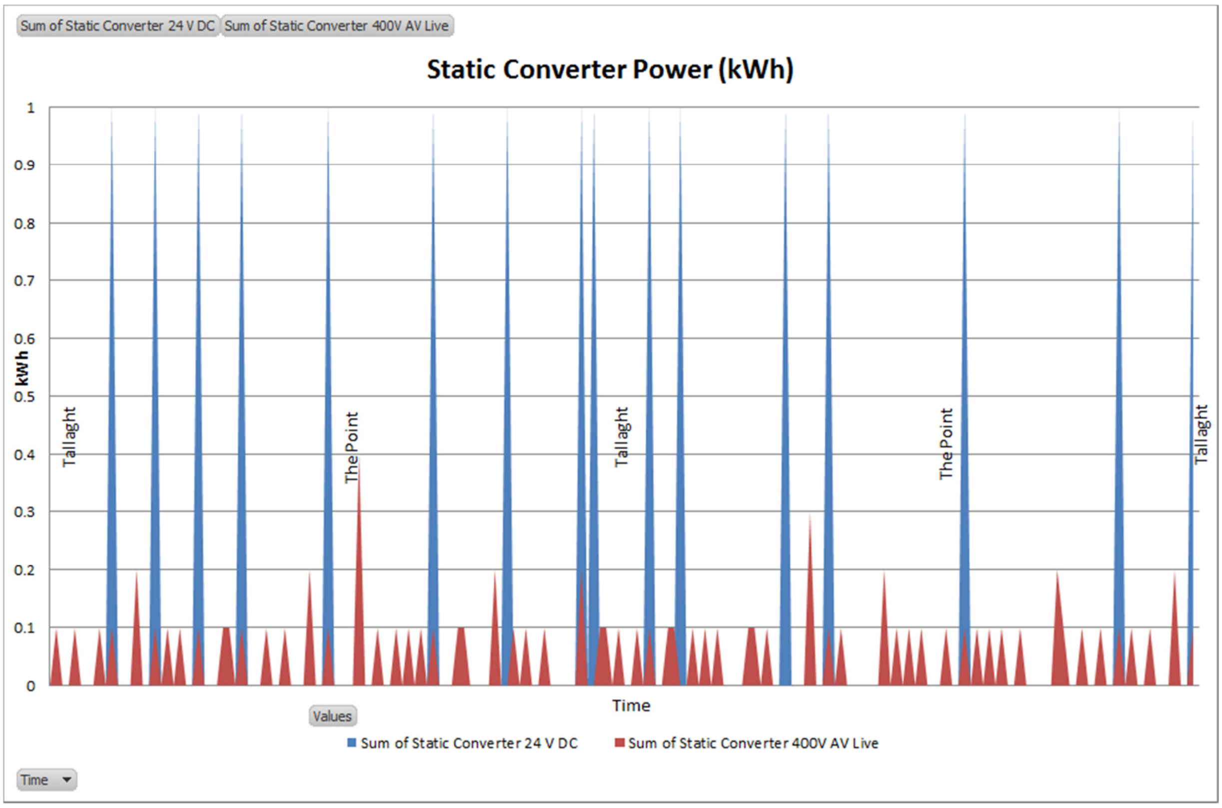


Figure 52: Static Converter Energy Consumption

4.1.5 Luas Energy Map

To better understand and forecast Luas energy consumption, an energy map of the Luas Red Line was created based on this research. This energy map outlined the energy consumption needs of vehicles in relation to the track profile. With this, Luas drivers could potentially be specifically trained to drive trams in the most efficient method specific to each section of track. In order to establish an energy map, the base line energy consumption per tram journey was established. To facilitate this process testing took place using an out of service tram vehicle. Testing took place between passenger service trams on the Red Line, to ensure normal operating conditions were maintained. The tram was driven in the pre-determined "efficient conditions" (previously adopted in the traction motor energy test) which yielded the lowest energy consumption results. The results of the energy map are detailed in the proceeding figures.

Figure 53 shows the speed profile for the in-bound journey. The speed on segregated sections of track is greater than shared sections of track. This can be seen in Figure 53, the first section of the track from the Tallaght stop in-bound is segregated and speeds reach 70 km/h. The remainder of the track is shared running in the city center locations. In these locations the speed was generally not greater than 30 km/h.

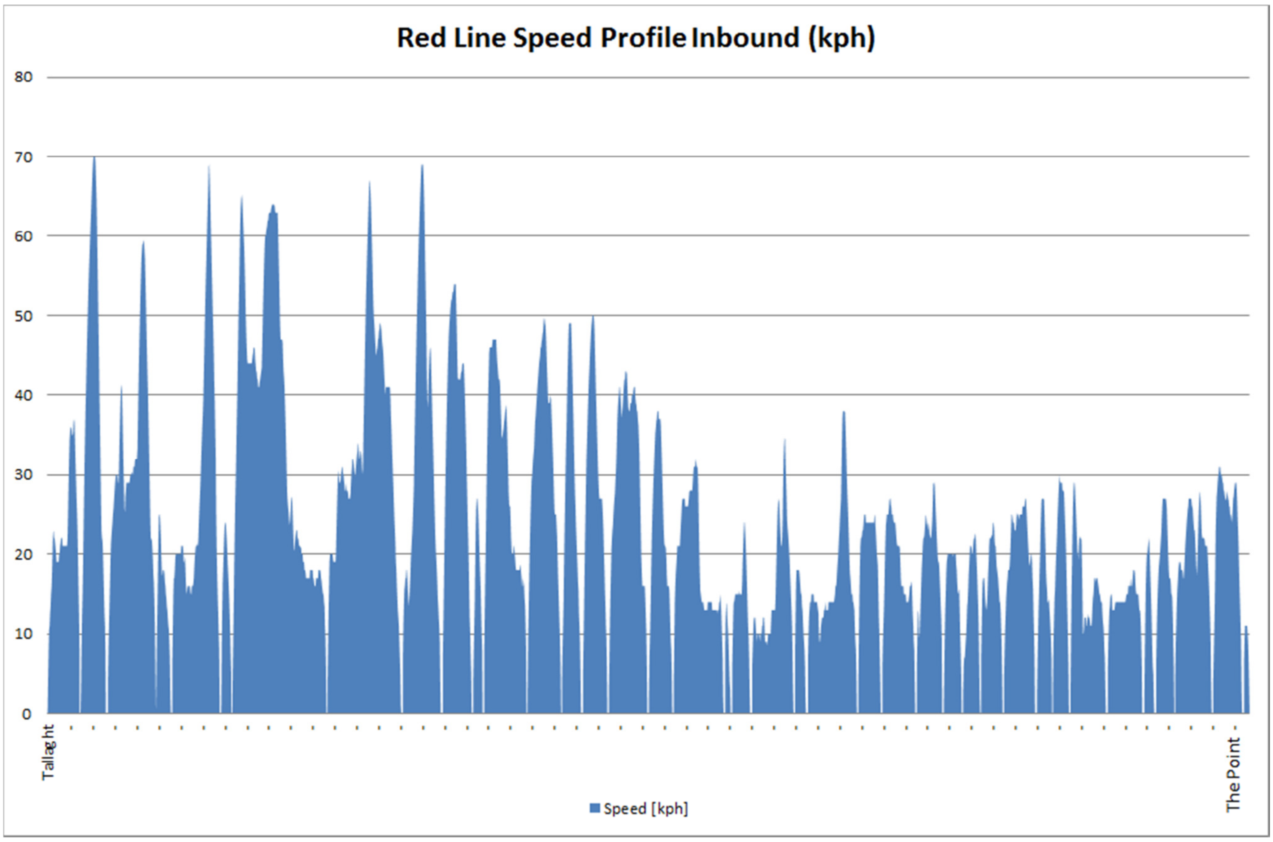


Figure 53: Red Line Speed Profile In-bound

Figure 54 shows the traction motor energy consumed for the in-bound journey. The graph shows the live energy consumption at one minute interval and also the total accumulated energy for the journey. In the segregated sections of track the energy consumption was higher due to the higher speeds achieved.

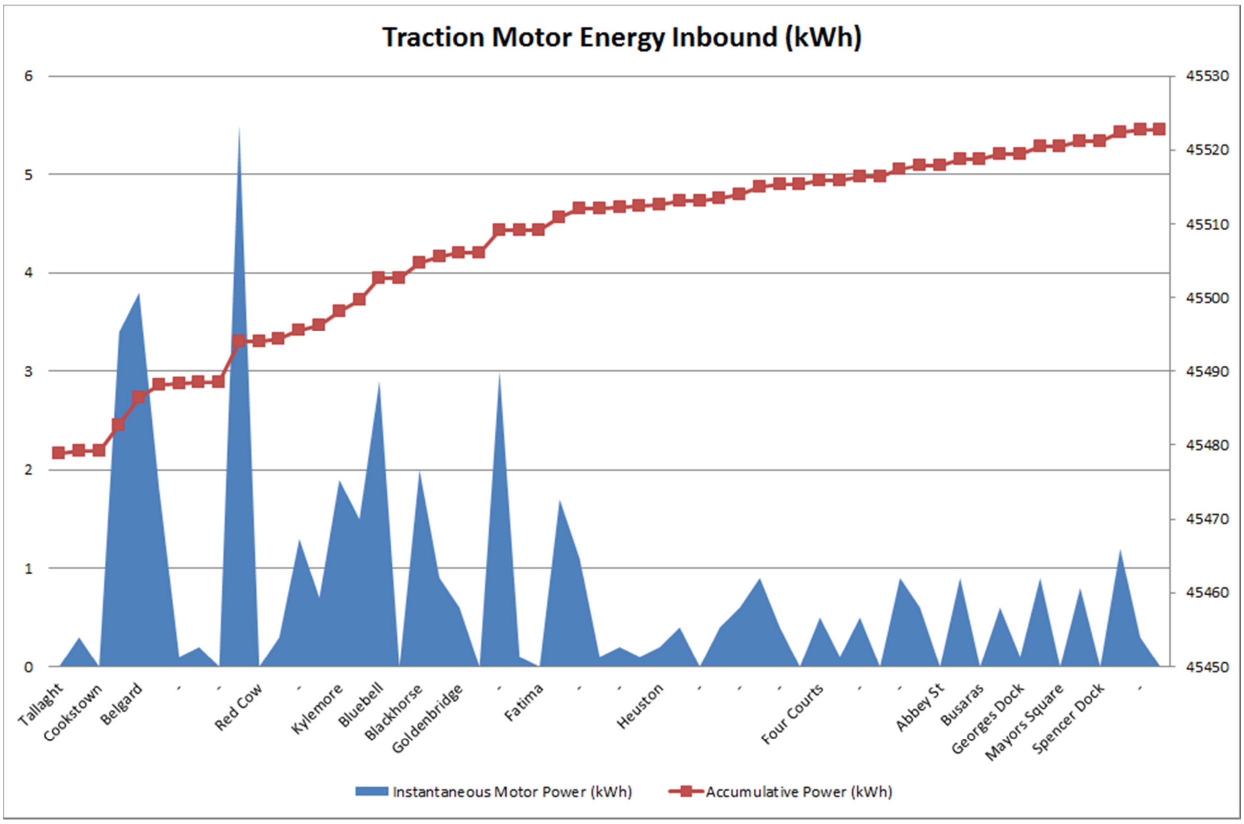


Figure 54: Traction Motor Energy In-bound

Figure 55 shows the regenerated power for the in-bound journey. The graph shows the live energy generated from braking and also the total accumulated energy for the journey. In the segregated sections of track increased energy was generated under braking as the tram was in braking mode for longer periods of time due to the higher speeds.

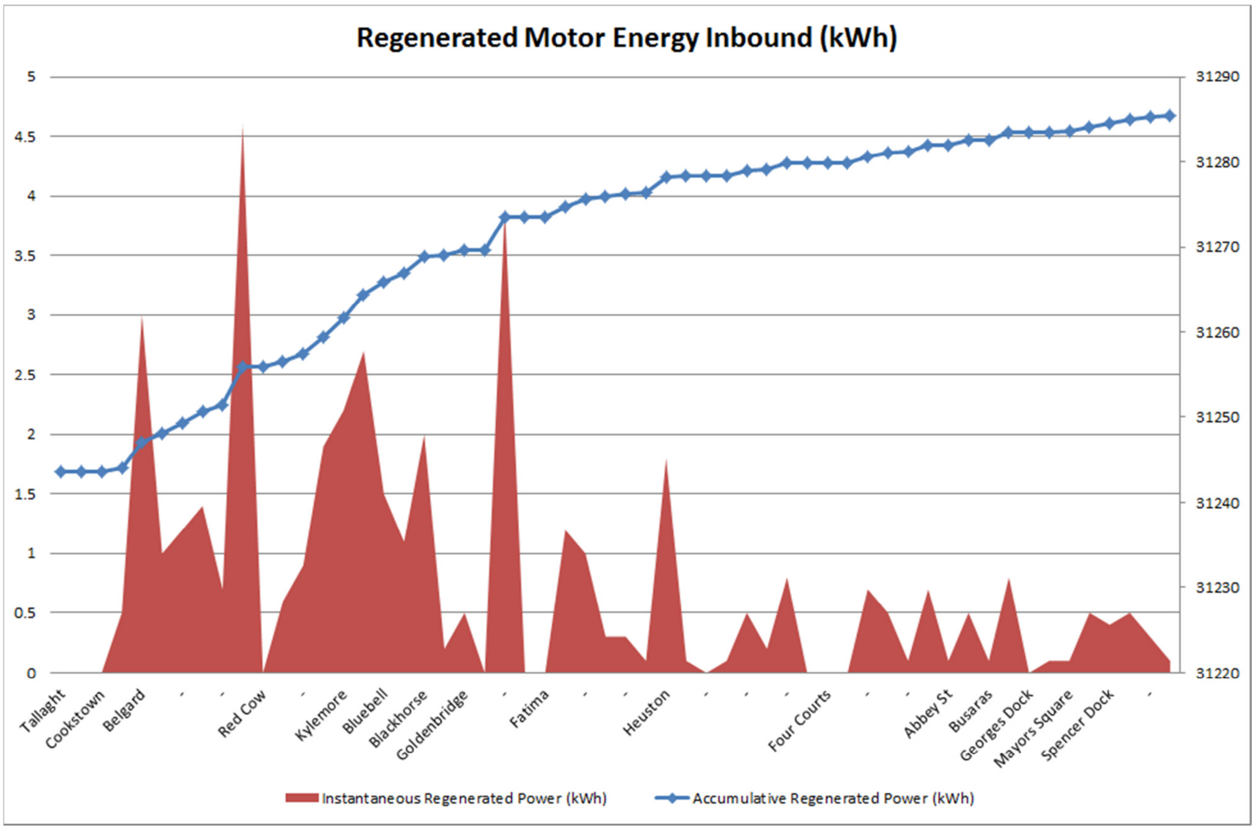


Figure 55: Regenerated Motor Energy In-bound

Figure 56 shows the static converter energy consumption for the in-bound journey. Driving styles did not have a direct impact on the energy consumption of the static converter which is used to power the tram system.

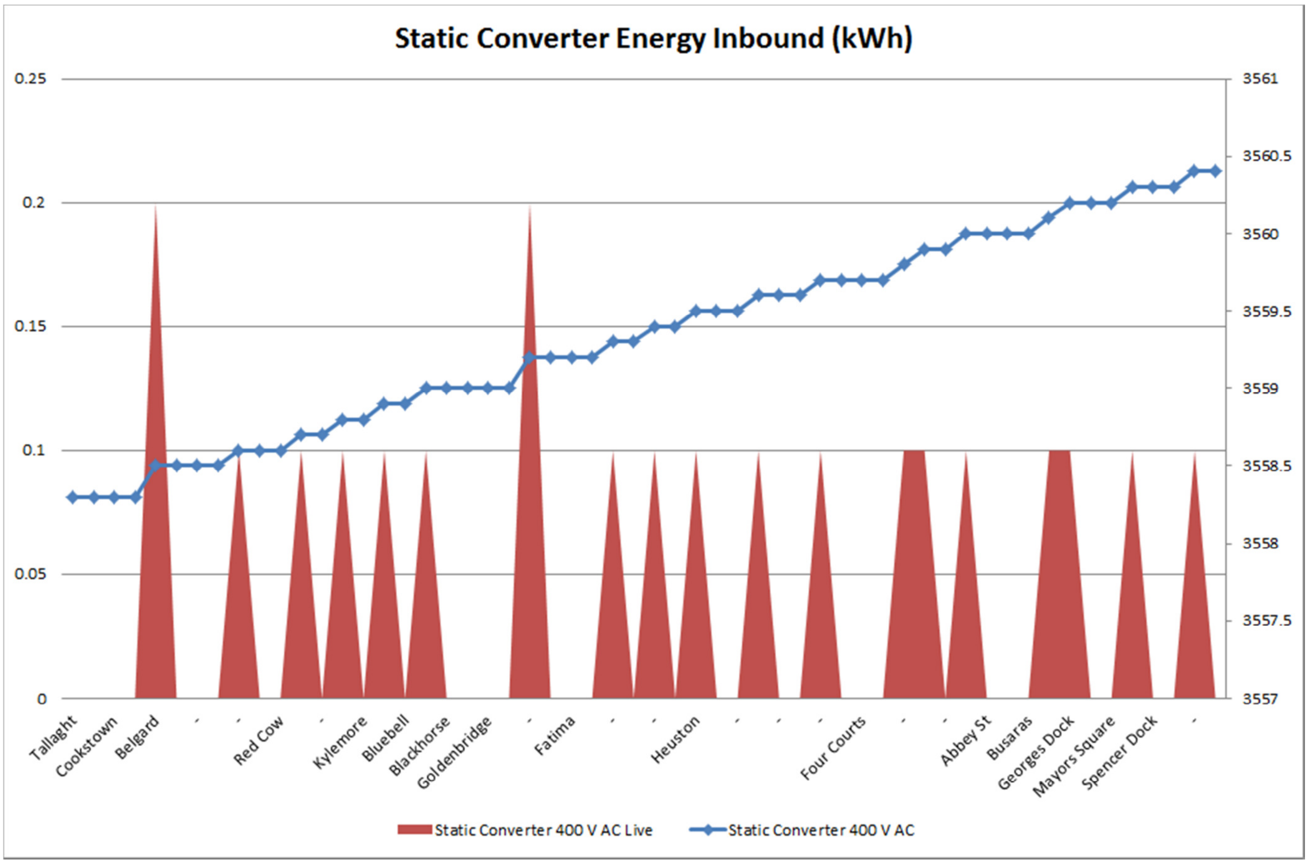


Figure 56: Static Converter Energy In-bound

Figure 57 illustrates the speed profile for the out-bound journey. The speeds are a mirror image of the in-bound journey in the opposite instance.

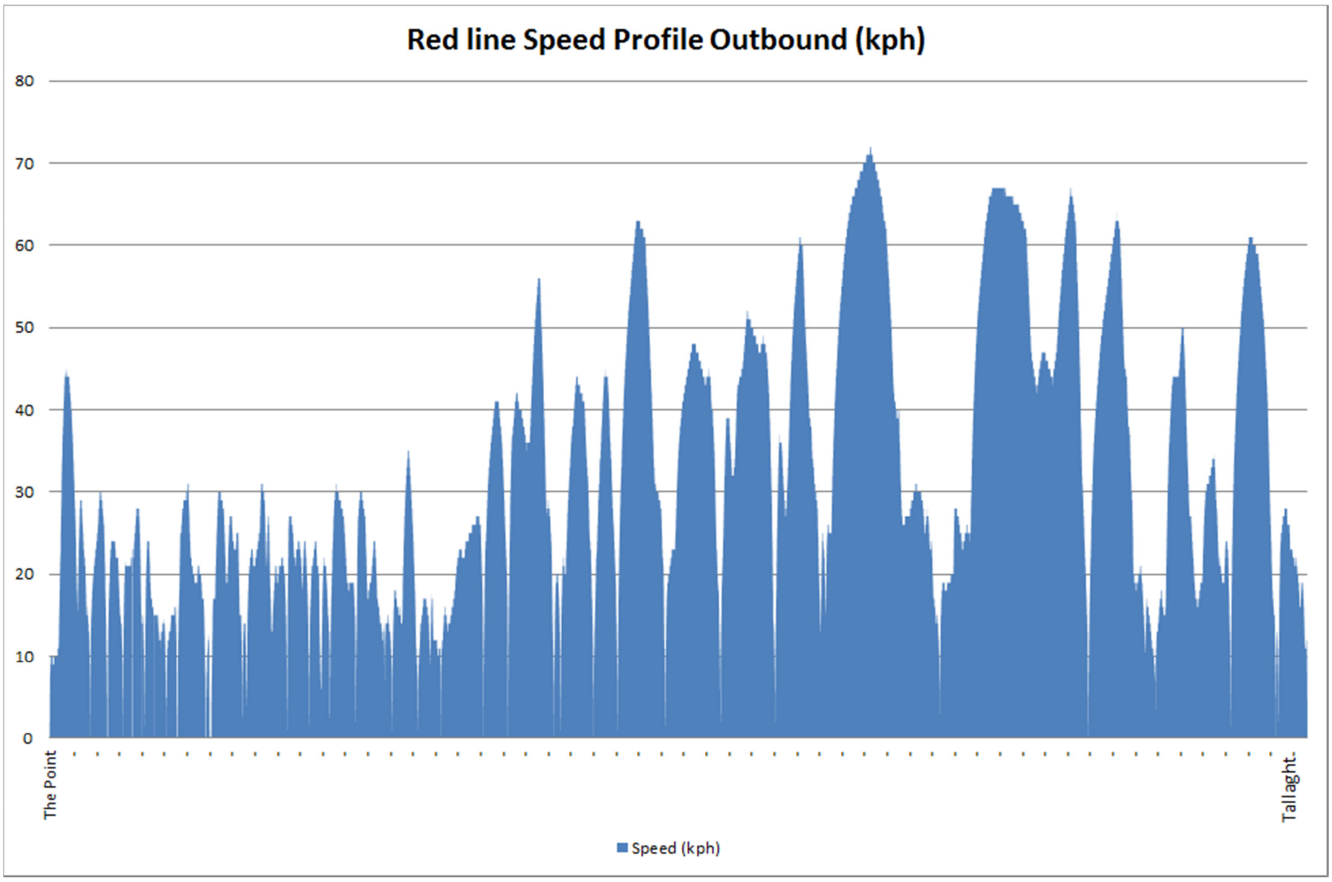


Figure 57: Red Line Speed Profile Out-bound

Figure 58 shows the traction motor energy consumption for the out-bound journey. Increased energy was consumed by the traction motors on the out-bound journey when compared to the in-bound journey. This is due to the increased gradient in the out-bound direction and also the higher speeds nearing the Tallaght stop.

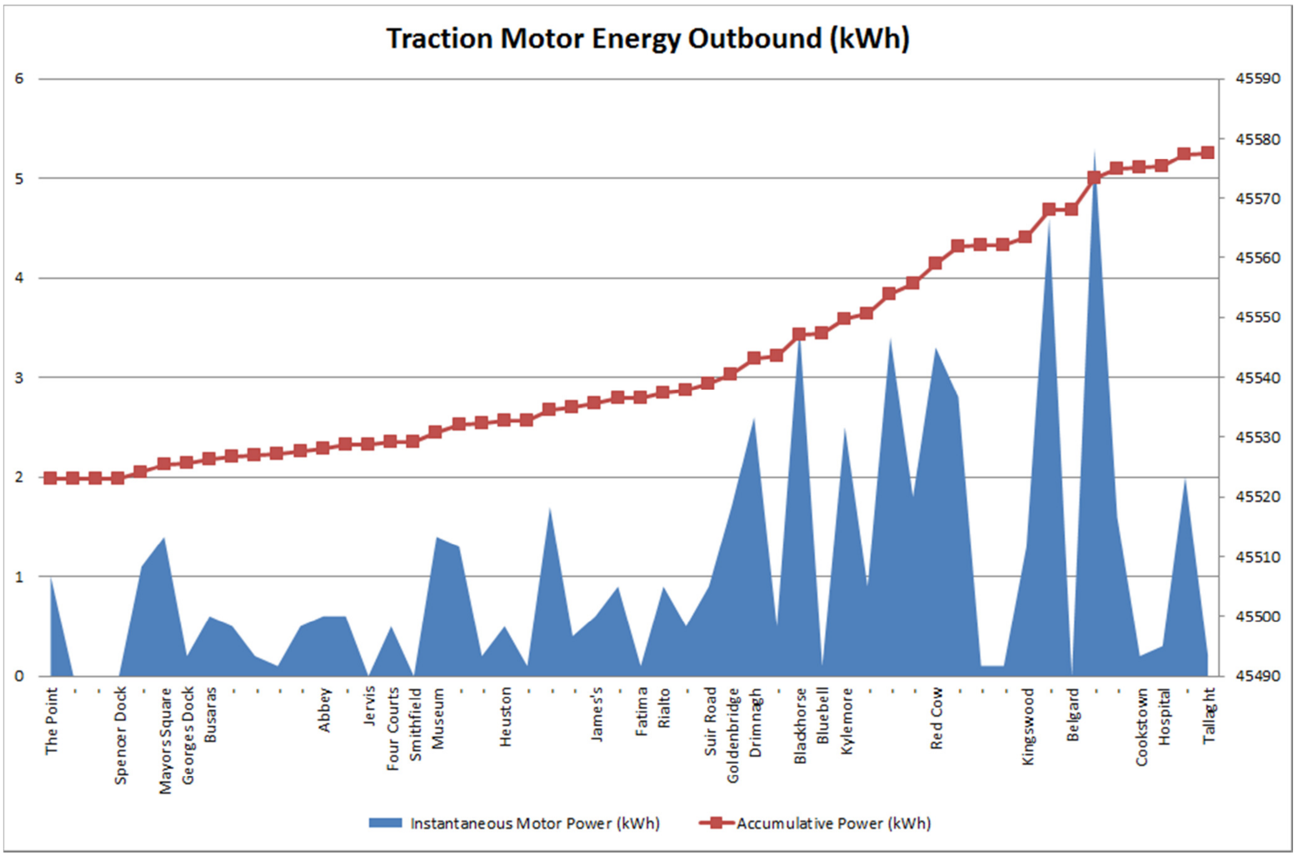


Figure 58: Traction Motor Energy Out-bound

Figure 59 shows the regenerated power for the out-bound journey. Less power was generated under braking for the outbound journey as the increased gradient in the out-bound journey aids in reducing the speed of the vehicle, resulting in less braking effort being required.

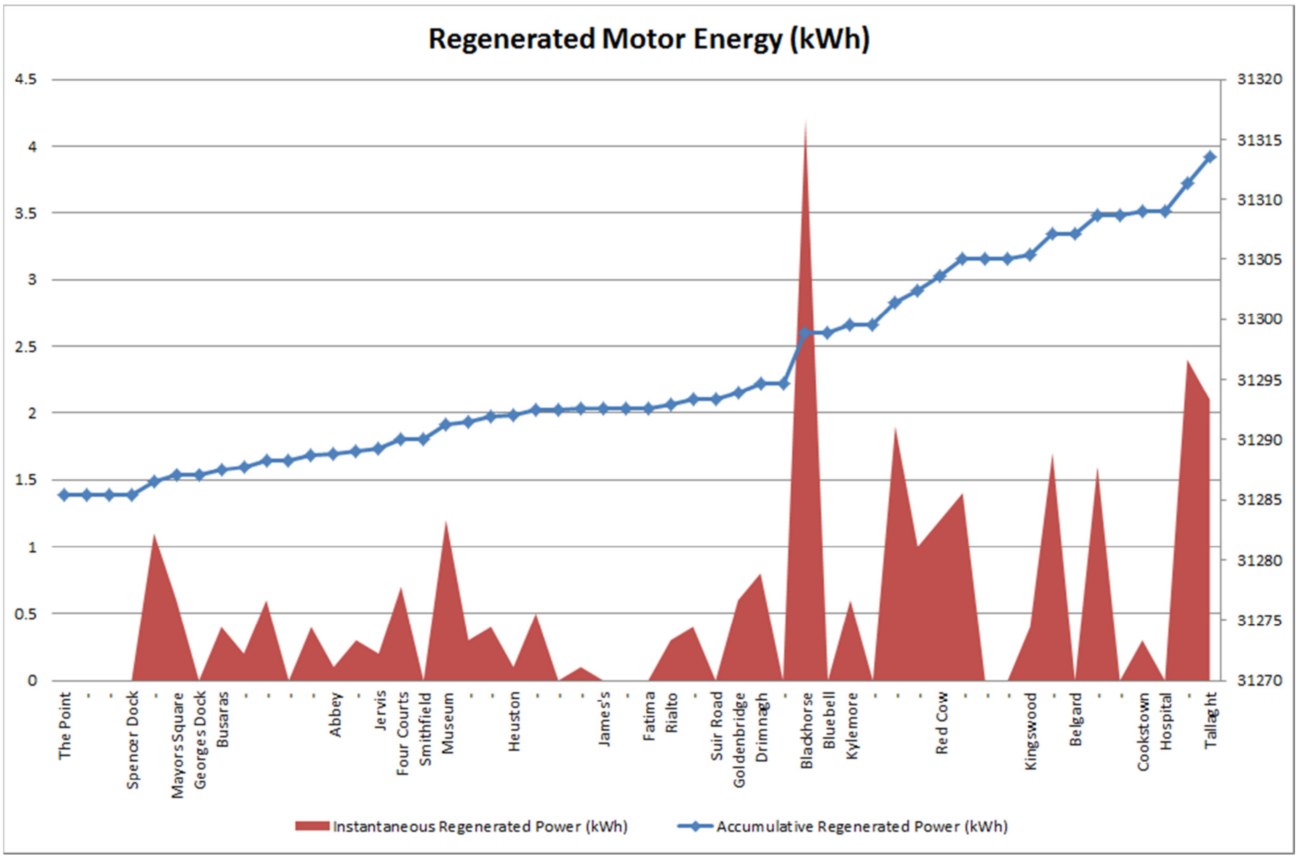


Figure 59: Regenerated Motor Energy Out-bound

Figure 60 illustrates the static converter energy consumption for the out-bound journey. As with the in-bound journey the static converter energy remains relatively constant.

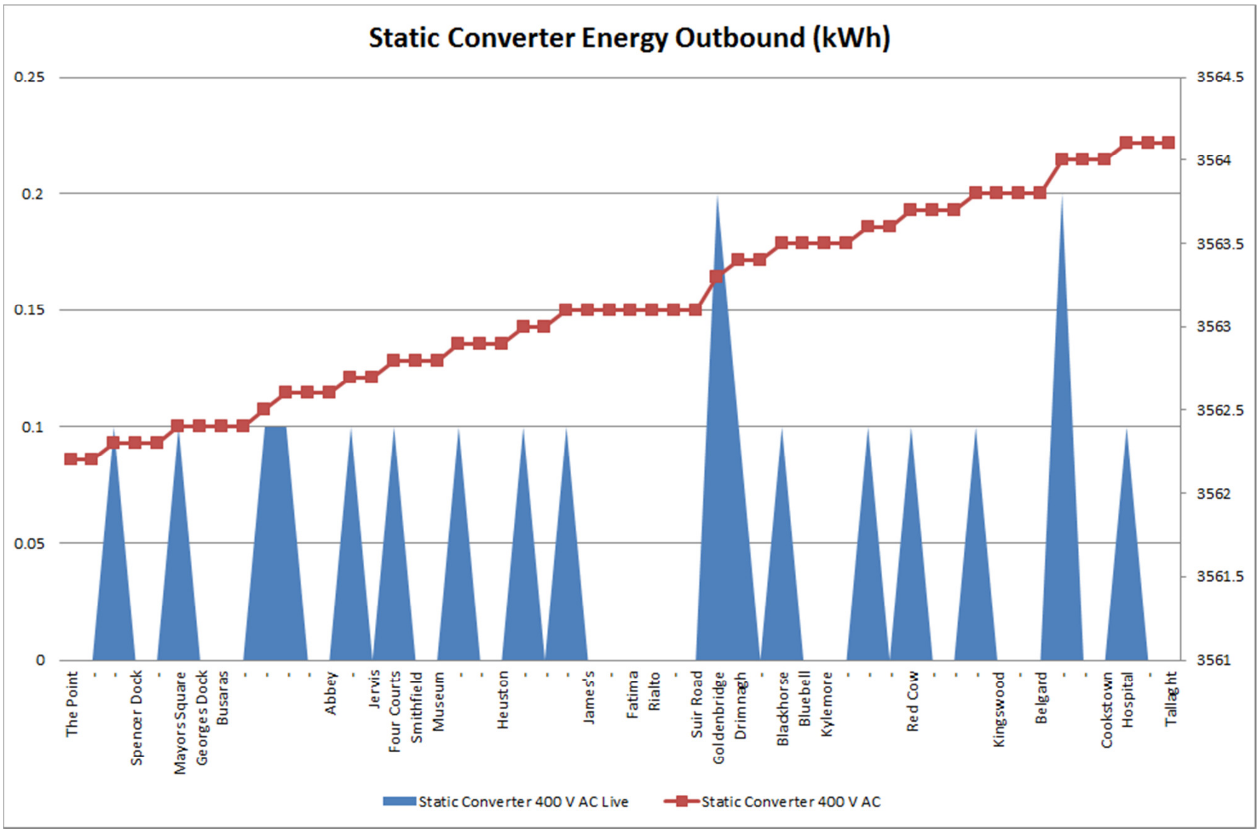
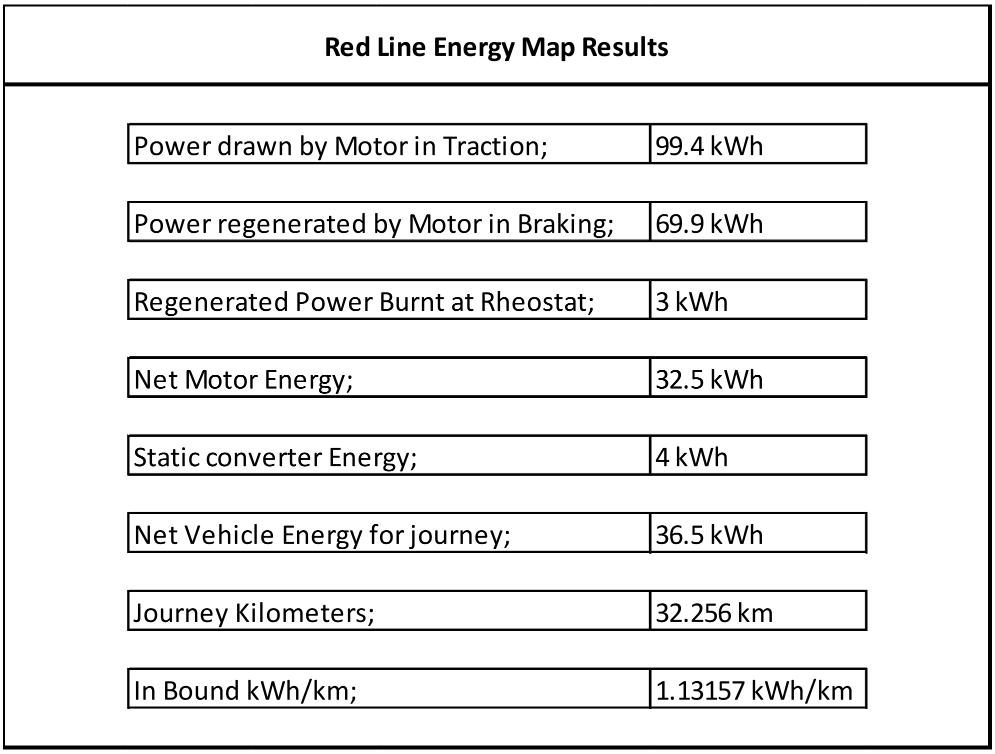


Figure 60: Static Converter Energy Out-bound

The energy consumption during the out-bound journey was, as expected considerably higher than the in-bound journey due to the gradient profile of the track. As a significant proportion of the Luas Red Line consists of shared running sections of track it was not always possible to maintain the specific efficient driving style at all times due to unexpected stops as a result of pedestrians of road vehicles on track sections. However the efficient driving style was maintained for the majority of the test. Table 13 indicates the results for the test, including a base line value of 1.13 kWh/km for the 32.3 km of track. This base line value was achieved employing an empty vehicle driving in an efficient manner during a normal passenger service time period. Trams operating with passengers on-board may have a higher consumption value due to passenger loads, this can be factored into any comparisons made between different drivers and operating conditions. The heating and ventilation energy consumption was omitted from this energy map as driving styles do not have an influence on its consumption. The value of 1.13 kWh/km achieved from this test, demonstrates the efficiency of Luas vehicle when driven in an efficient approach.

Table 13: Combined Testing Results



Red Line Energy Map Results

Power drawn by Motor in Traction;	99.4 kWh
Power regenerated by Motor in Braking;	69.9 kWh
Regenerated Power Burnt at Rheostat;	3 kWh
Net Motor Energy;	32.5 kWh
Static converter Energy;	4 kWh
Net Vehicle Energy for journey;	36.5 kWh
Journey Kilometers;	32.256 km
In Bound kWh/km;	1.13157 kWh/km

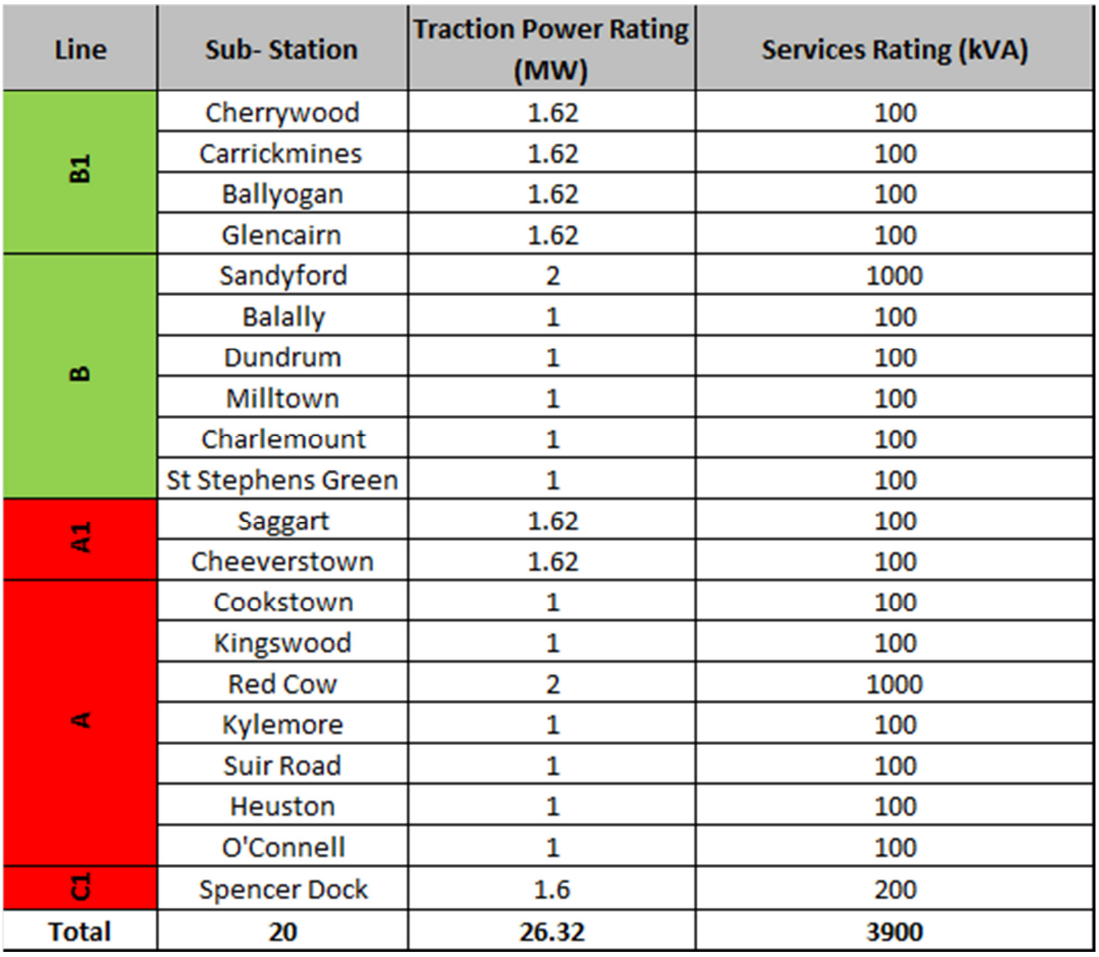
4.2 Infrastructure

Luas infrastructure including sub-stations, Luas depots and Luas stops encompass systems and components which consume energy. This section of the research analyses Luas infrastructure energy consumption.

4.2.1 Sub-Stations

The Luas system has 20 sub-stations positioned at regular intervals on the Red and Green line. These sub-stations provide a continuous nominal voltage of 750 V DC to the OCS for use by tram vehicles. In total Luas sub-station have a capacity of 26.3 MW as detailed in Table 14. Sub-stations also provide power for services located within each sub-station, such as ventilation systems and the backup uninterruptable power supplies (UPS) [99]. Some sub-stations located adjacent to Luas stops also provide auxiliary power for stop equipment.

Table 14: Luas Sub-station Power Ratings



Line	Sub- Station	Traction Power Rating (MW)	Services Rating (kVA)
B1	Cherrywood	1.62	100
	Carrickmines	1.62	100
	Ballyogan	1.62	100
	Glencairn	1.62	100
B	Sandyford	2	1000
	Balally	1	100
	Dundrum	1	100
	Milltown	1	100
	Charlemount	1	100
	St Stephens Green	1	100
A1	Saggart	1.62	100
	Cheeverstown	1.62	100
A	Cookstown	1	100
	Kingswood	1	100
	Red Cow	2	1000
	Kylemore	1	100
	Suir Road	1	100
	Heuston	1	100
	O'Connell	1	100
C1	Spencer Dock	1.6	200
Total	**20**	**26.32**	**3900**

Each sub-station across the Luas system consumes different amounts of energy per day based on factors such as its location and auxiliary requirements. The two sub-stations at each of the Luas depots have the highest consumption of the system as they provide traction power to the main line and also provide traction power to the depot storage lanes and workshops, as well as 400 V AC supply to the depot buildings. The sub-stations which supply power to the end of line shunt also have higher consumption to those located along the main line, as up to two trams may potentially spend a maximum of twenty minutes idle at the end of the line shunt before departing on the next service. During this time the trams will be prepped with the saloon lighting and heating and ventilation system active, which may, in winter months consume significant amounts of energy. Each sub-station has a quarter hour metering system installed which is managed by the Meter Registration System Operator (MRSO) on behalf of the energy provider. Figure 61 shows the total Luas medium voltage energy consumption supplied through the sub-stations from 2011 to 2014 [100].

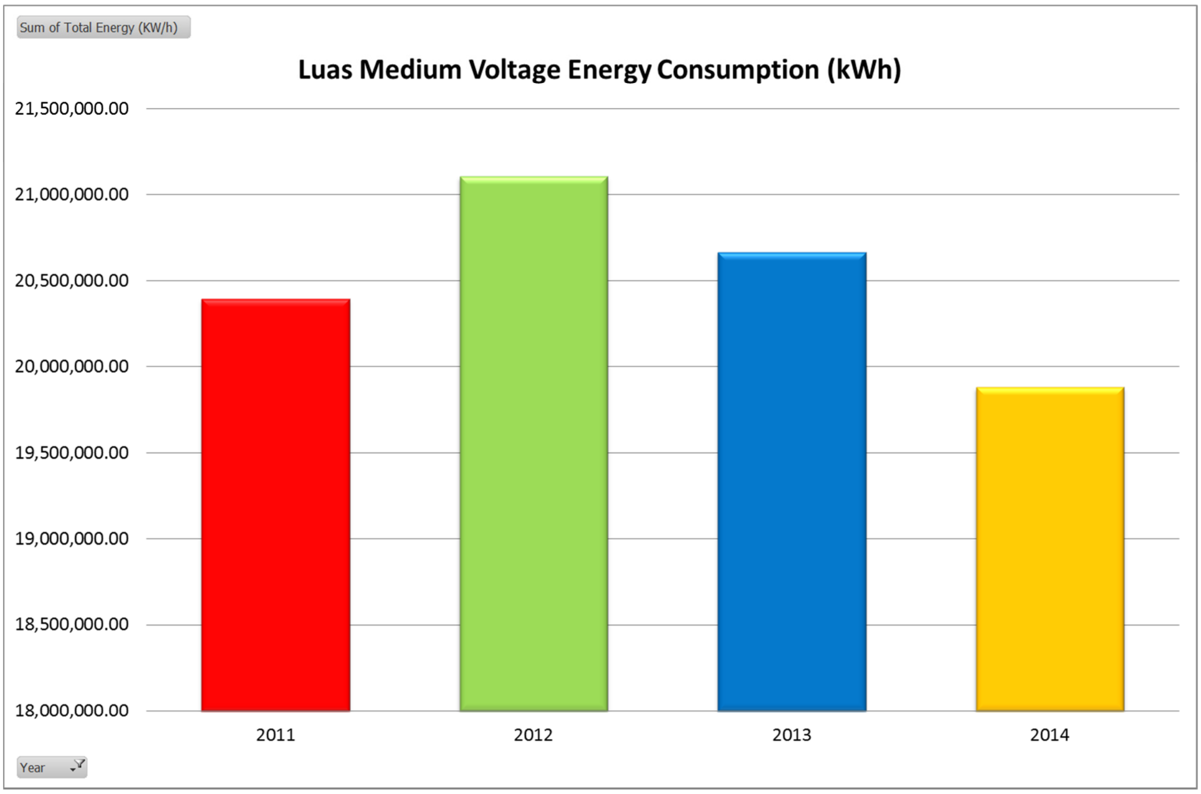


Figure 61: Total Luas Energy Consumption

Figure 62 illustrates the total energy consumption of the Red line to be 42% more than the Green Line in 2013. This is due to a longer section of track, a larger fleet and increased passenger service operations on the Red Line [100].

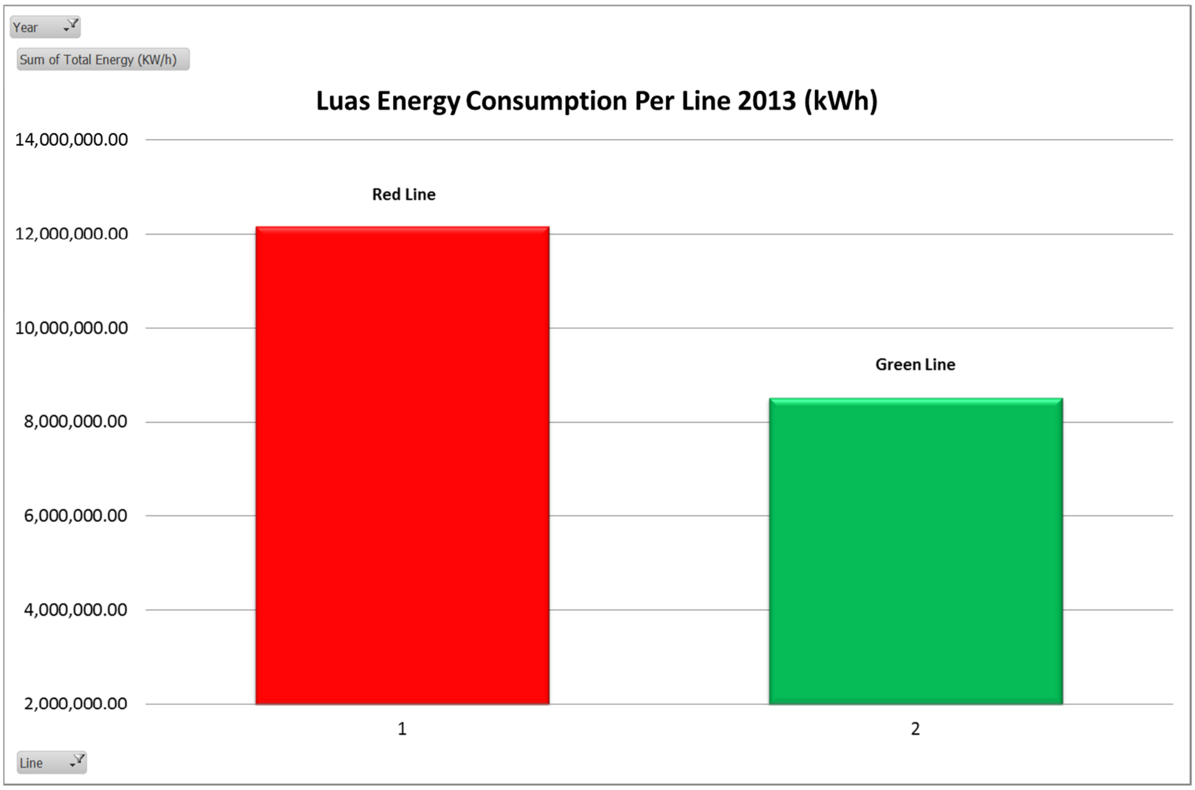


Figure 62: Luas Energy Consumption per Line 2013

Figures 63 and 64 indicate the energy consumption per sub-station for the Red and Green Lines during 2013. Depots located at the Red Cow and Sandyford consume significantly more energy than main line sub-stations. The Red Cow sub-station consumed 50% more than the highest main line sub-station. Sandyford also consumed 20% more than the highest main line sub-station on the Green Line [100]. Dundrum sub-station was out of commission during 2013 and as such did not consume any energy.

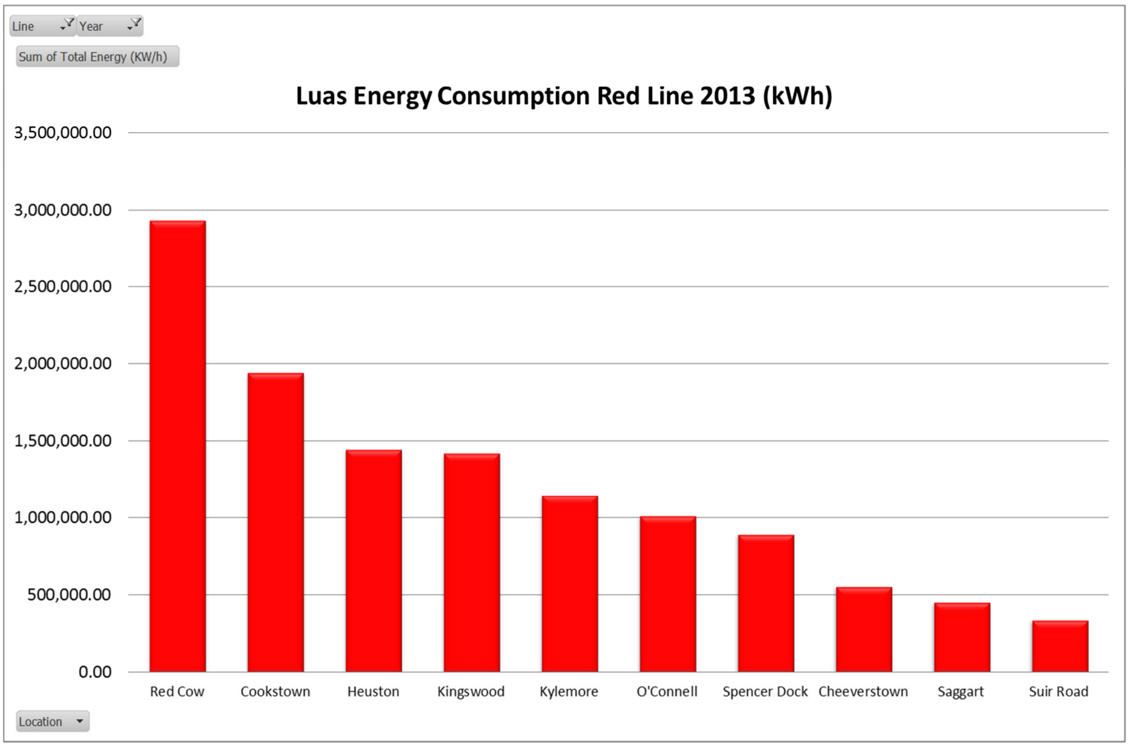


Figure 63: Luas Energy Consumption Red Line Sub-station 2013

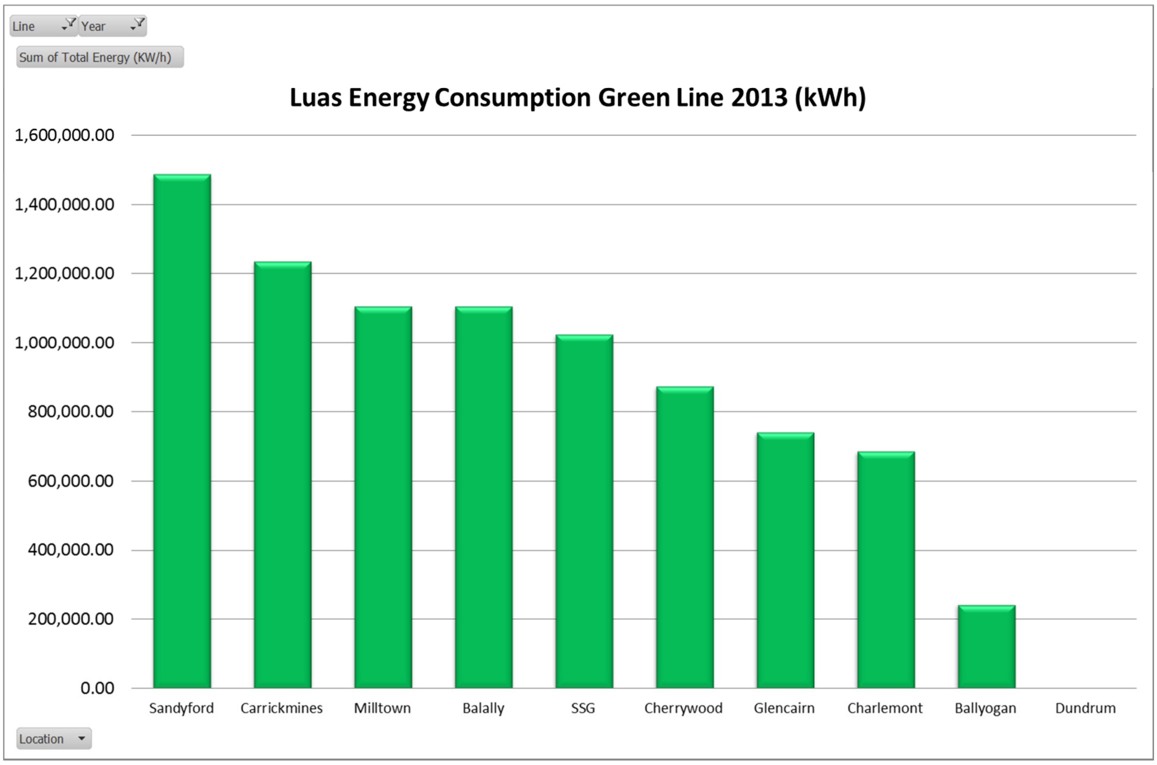


Figure 64: Luas Energy Consumption Green Line Sub-station 2013

Figure 65 details the monthly breakdown of total energy consumption across both lines for 2013. The energy consumption increases across both lines during winter months are largely due to the increased use of the on-board heating and ventilation systems [100].

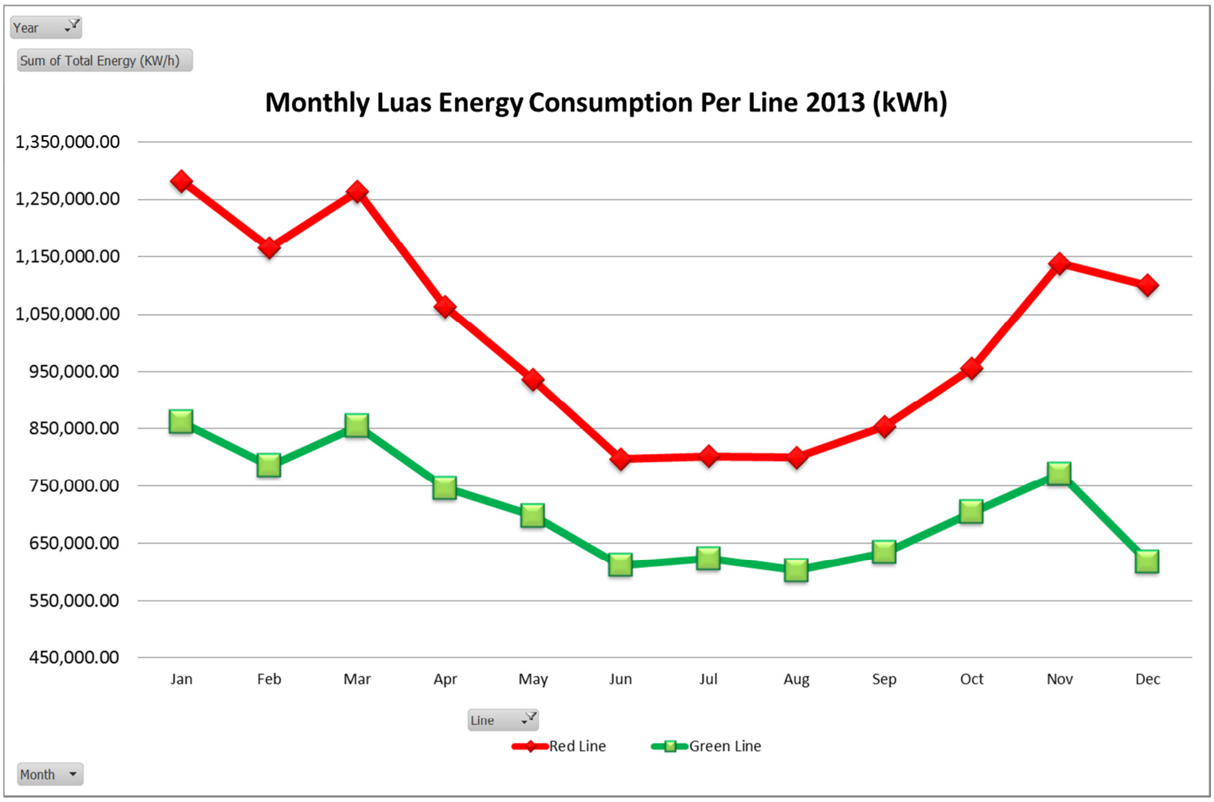


Figure 65: Monthly Luas Energy Consumption 2013

4.2.2 Luas Stops

Luas has a total of 54 stops across the system, 22 on the Green Line and 32 on the Red Line. Luas stops provide a platform for passengers to board and alight Luas trams. Each stop has a range of facilities for travelling passengers. These facilities include ticket vending machines, ticked validators, parking meters, passenger information displays, emergency help points, lighting, shelter and seating. The Luas system also has a total of seven park and ride facilities, four on the Green Line and three on the Red Line. Power is supplied to Luas stops and park and ride facilities in one of two ways. The first is by an auxiliary transformer located in an adjacent sub-station to the stop. If there is no sub-station located adjacent to the stop, power is supplied directly from the main electrical grid via an electrical cubicle [101]. Depending on the size of the stop or park and ride and the facilities installed, the energy consumption of each may differ greatly. The Connolly stop on the Luas Red Line for example is one of the biggest on the system with a large number of lights and also two escalators, as such it is the highest consumer of energy on the Red Line. Figure 66 shows the total energy consumption for Luas Red line stops in 2013 which have a direct supply from the grid [102].

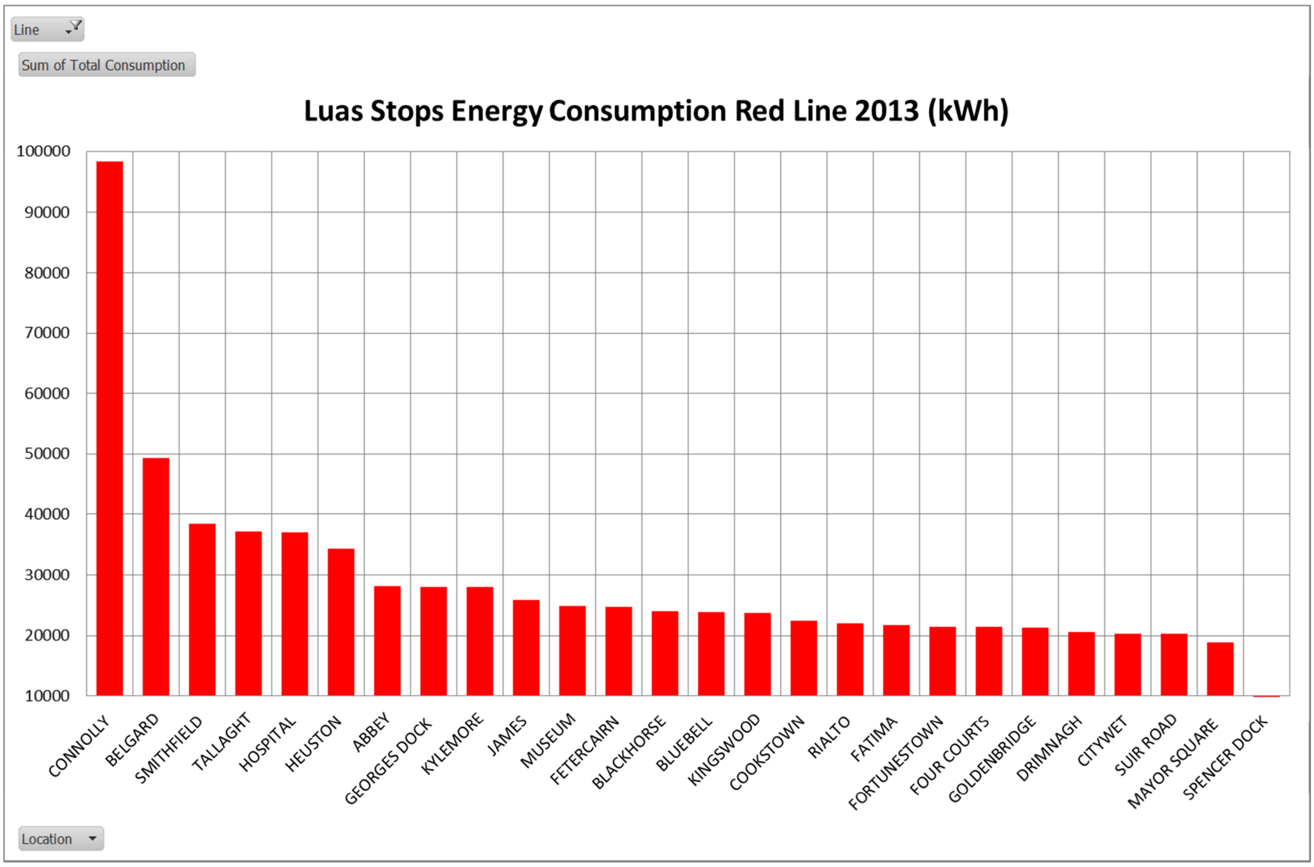


Figure 66: Luas Stops Energy Consumption Red Line Stops 2013

Figure 67 shows the total energy consumption of the Luas Green line stops in 2013 [102].

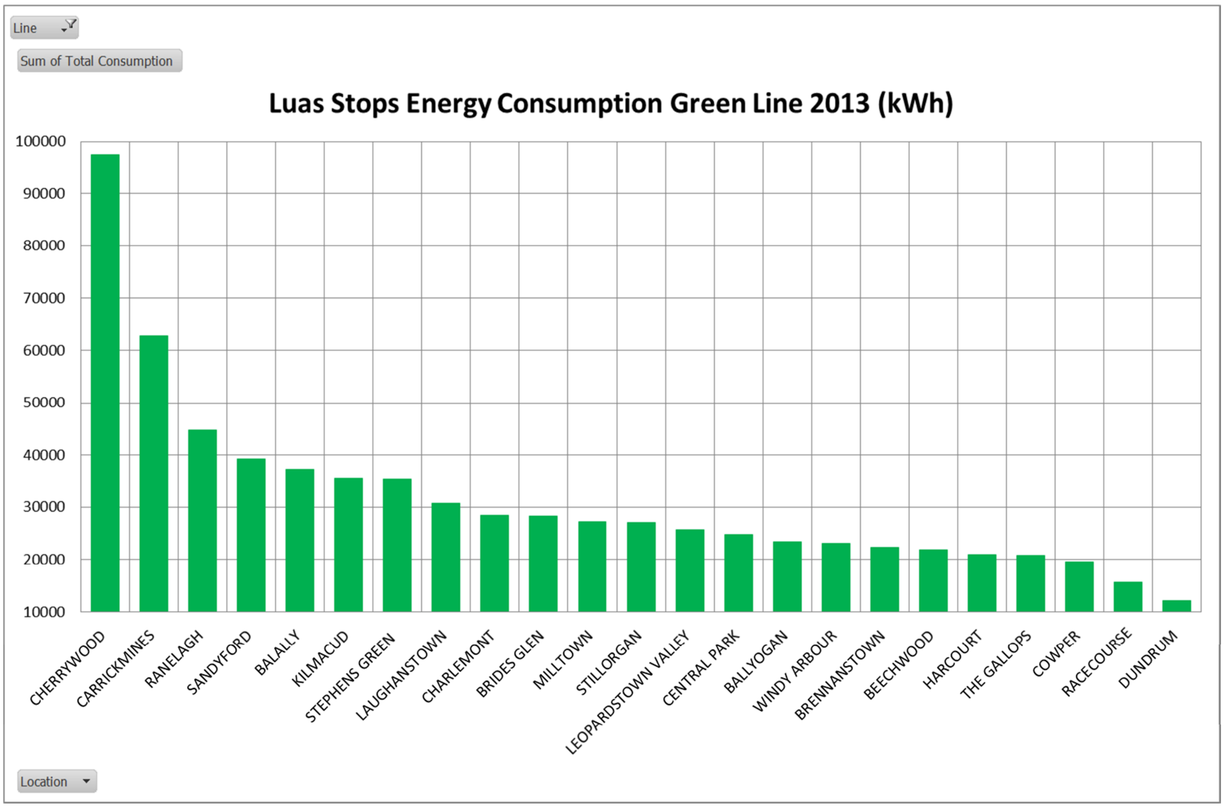


Figure 67: Luas Stops Energy Consumption Green Line Stops 2013

4.2.3 Luas Depots

Luas has two depots located at the Red Cow and Sandyford. Depots house trams during periods of non-passenger operations and provide maintenance facilities and office space. Both depots sub-stations provide 750 V DC power to the main line and to the depot storage and workshop OCS. An essential auxiliary transformer location within the sub-station supplies 400 V AC power to the central control room and server rooms. A non-essential auxiliary transformer also supplies 400 V AC power to the maintenance and office areas. As a result the depot sub-station energy consumption is considerably higher than the main line sub-stations [103]. Depot consumption can vary significantly due to a number of factors. Weather conditions have the single biggest impact on Luas energy consumption. During winter months the activation of the heating and ventilation systems on trams stable in the depot results in increased energy consumption. During extreme weather conditions Luas vehicles are prepped (switched on) in the depot storage area up to 30 minutes before they are due to enter passenger storage in order to keep the OCS free of ice and to ensure the reliability of the fleet pre-departure. This process has a negative impact on energy consumption as a fully prepped stable tram can consume up to 100 kWh in cold weather conditions [104]. Figure 68 represents Luas depot energy consumption from 2011 to 2014. It is evident that the Red Cow depot consumption is somewhat higher than the Sandyford depot, this is due to the higher number of trams at the Red Cow (40 versus 26) and the larger maintenance workshop and office area.

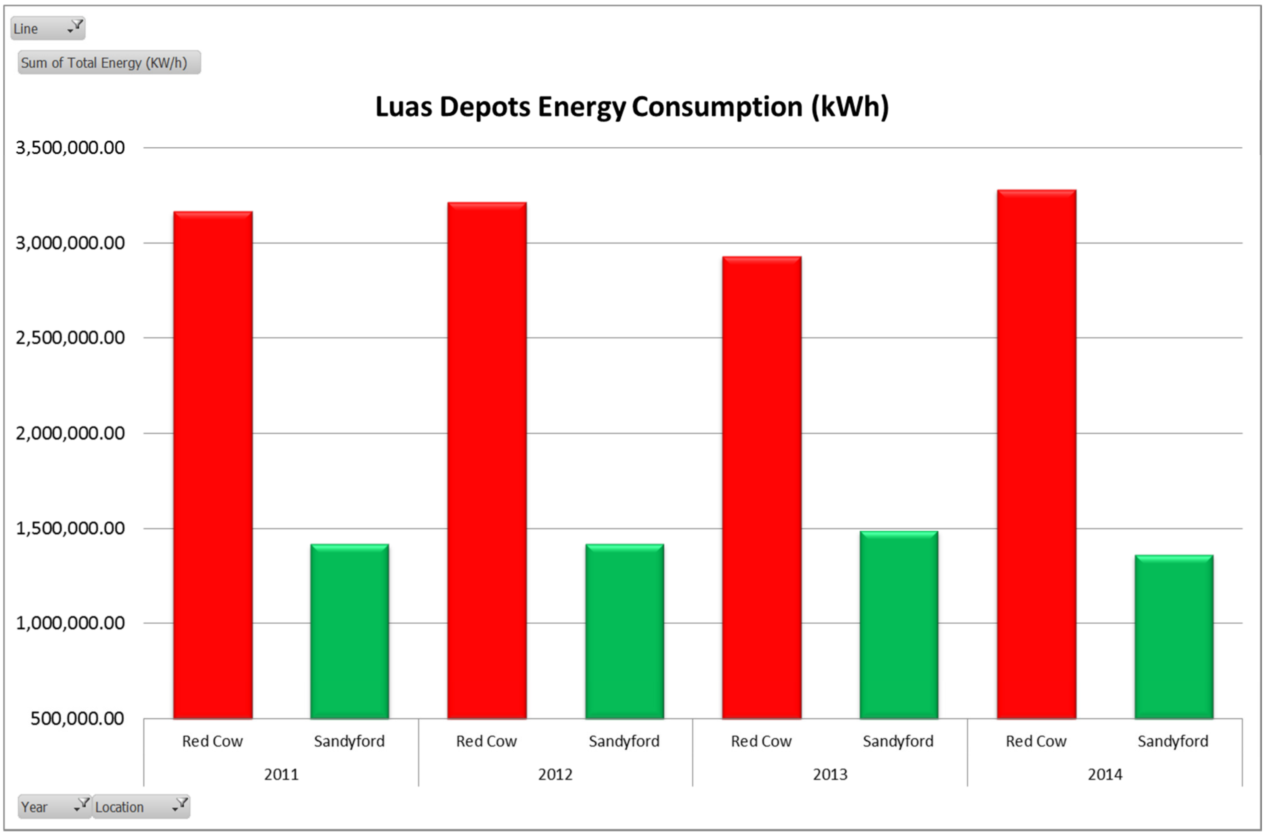


Figure 68: Luas Depot Energy Consumption

Figure 69 shows the monthly breakdown of depot energy consumption in 2013. Similar to that of main line sub-stations, depot energy consumption is lowest during summer months where external temperatures are generally higher than that of winter months [105].

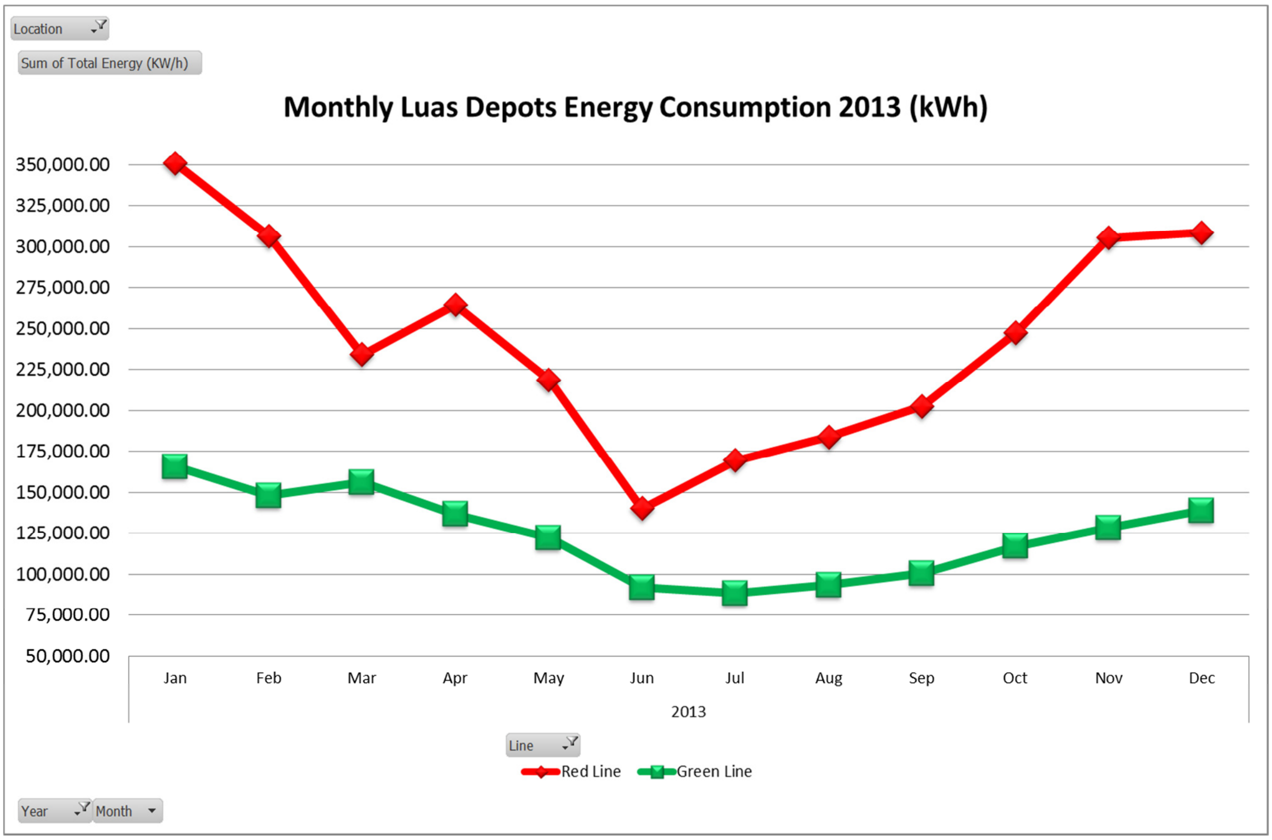


Figure 69: Luas Depot Monthly Energy Consumption 2013

4.3 Factors Influencing Luas Energy Consumption

Many factors influence the total energy consumption of Luas operations from year to year. Over the past number of years Luas has increased its network and fleet. Passenger operations have also changed a number of times in the past three years. This section of the thesis explores the non-technical factors influencing Luas energy consumption.

4.3.1 Luas Network Increases

Total energy consumption of the Luas Red Line has progressively increased from 2009. This increase can be contributed to two main factors. The Luas Red line has been extended on two occasions, opening a 4 km section of track in 2009, and a 5 km section of track in 2011. During this period the fleet has also increased from 26 trams to 40 trams. These network extensions and increase in fleet size has resulted in increased passenger service operations. The total number of annual kilometres operated has almost doubled in the same period. From Figure 70 the impact these extensions, fleet increases and operational increases has had on energy consumption is evident [106].

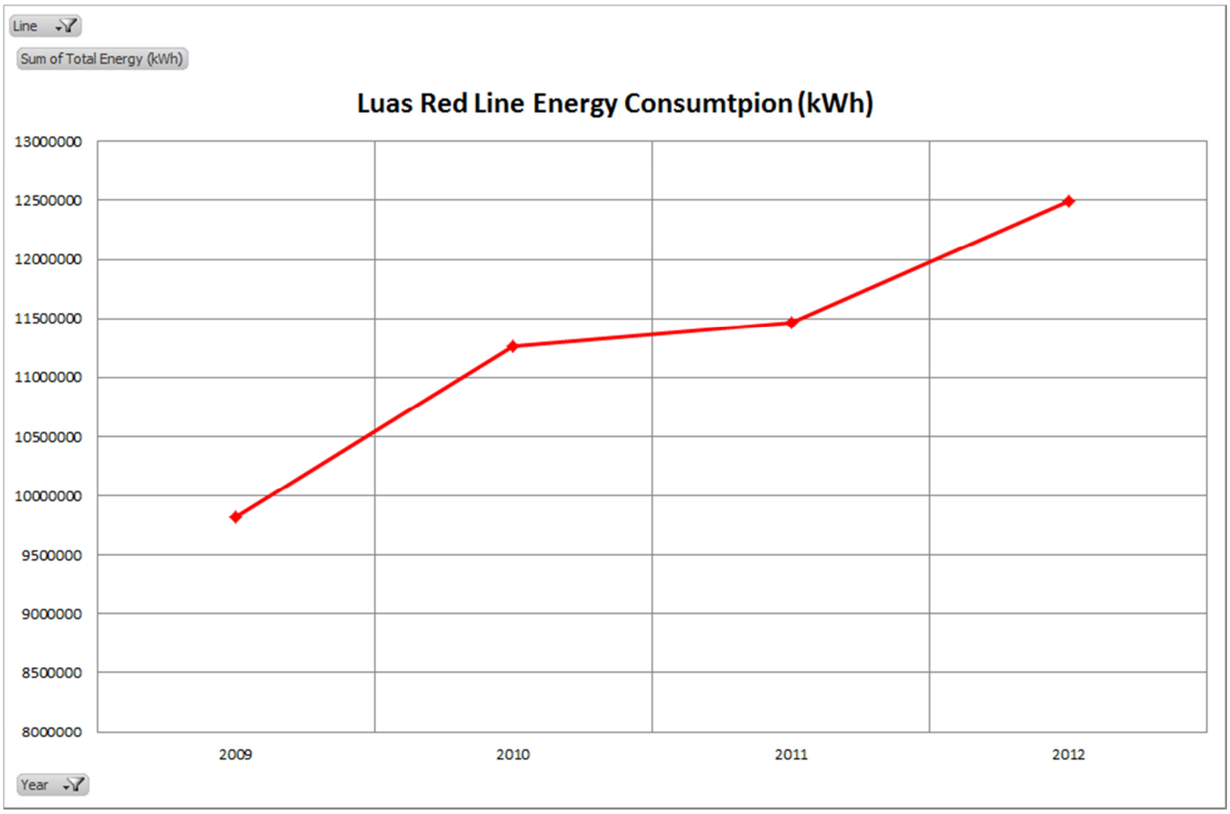


Figure 70: Luas Red Line Energy Consumption Increases

The Luas Green Line was also extended from Sandyford to Cherrywood in 2010. This 6 km section of track increased the network by almost 70%. From 2009 to 2012 the Green line fleet also increased from 14 to 26 trams. As a result the total energy consumption of the Green line increased year on year from 2009 to 2011. In 2012 the total energy consumption decreased slightly due to a reduced service being operated. Figure 71 indicates the energy consumption increases up to 2011 as a result of the network and fleet extensions, and the energy consumption decrease in 2012.

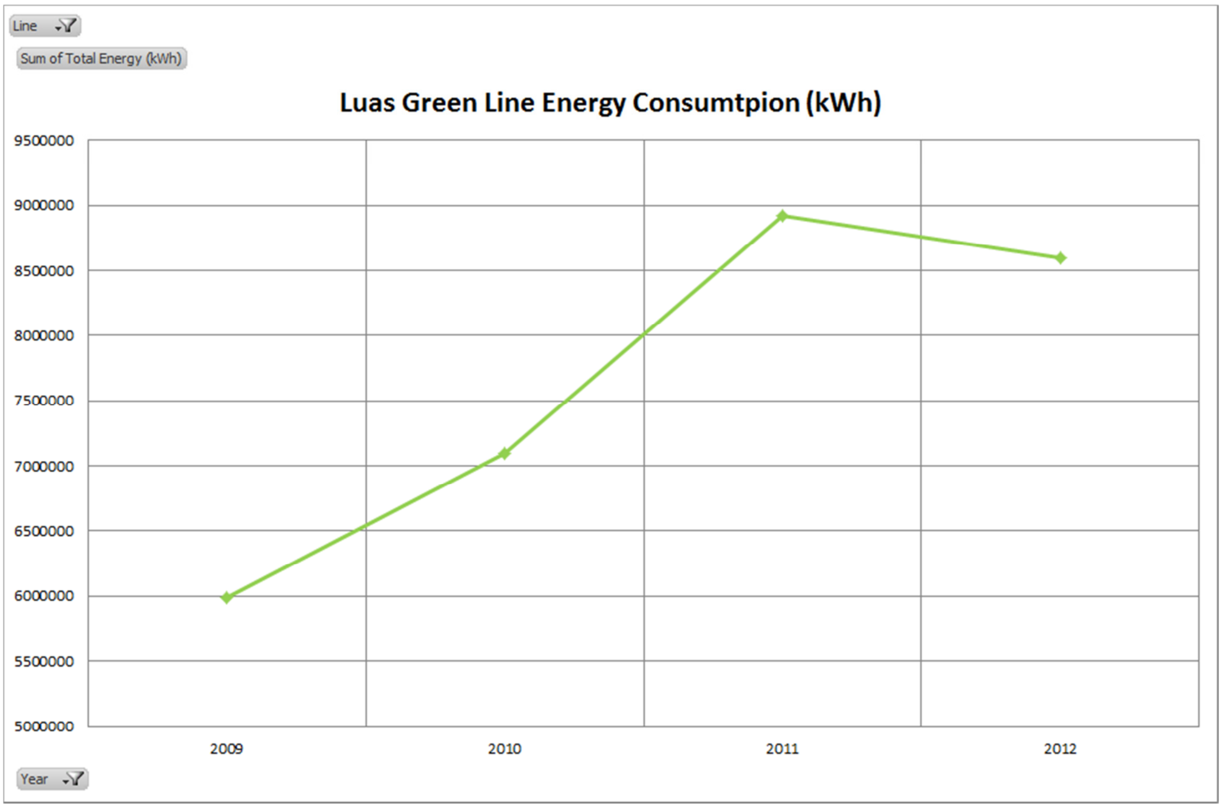


Figure 71: Green Line Energy Consumption Increases

The energy consumption of the Luas system as a whole has steadily increased from 2009 onwards. Luas now consumes in excess of 21,000,000 kWh per year. In order to sustain a viable transport system Luas must contain and where possible reduce its overall energy consumption. In 2017 the Luas cross city extension will begin passenger operations. Luas cross city will be a 6 km extension to the Green Line with two further sub-stations and a depot being constructed. The Green Line fleet will also increase from 26 to 32 trams [107].

4.3.2 Operational Influences

Luas passenger operations have the biggest impact on the total energy consumption in any given year. The number of kilometres, number of trams in operation and operational frequencies are the main contributing factors for energy consumption. At present Luas operates two set frequencies. Weekday peak operations have between 4 and 10 minute headways, and off-peak operations have between 10 and 15 minute headway frequencies. Weekend peak operations have 12 minute headways, and weekend off-peak operations have between 12 and 15 minute headway frequencies. The number of trams required for this operation on the Red Line is 26 for the AM peak and 24 for the PM peak service. The Green line operations require 20 trams for service during AM peak and 14 during PM peak [89]. Should the operating timetable or frequency be increased or decreased there would be a subsequent impact on the overall energy consumption of the system. Other operational disruptions such as planned or un-planned shutdowns of the system due to maintenance or safety related instances, has an effect on the overall energy consumption. In late 2011, Dundrum sub-station was flooded due to heavy rain. The flooding rendered the sub-station out of commission for over 18 months [107]. During this period the neighbouring two sub-stations at Balally and Milltown provided the 750 V DC power to the section of track Dundrum would normally power. When analysing the energy consumption for Balally sub-station an increase of 43% was recoded, an increase in the Milltown sub-station of 73% was also noted for 2012. However this percentage increase was not equal to the amount of power Dundrum sub-station would normally provide, it was some 39% less [100]. Other day to day disruptions would have a more localised effect on energy consumption. In May of 2013, the platform canopy at the Belgard Luas stop had to be replaced over a weekend (04/05/2013–06/05/2013). This resulted in Luas only operating passenger services for a proportion of the Red Line. As such the total kilometres and trams operated over the weekend was reduced. Figure 72 highlights the reduction in overall energy consumption for these days due to the shutdown of a proportion of the system. On average over the three days the total energy consumption of the entire Red Line was reduced by 54%.

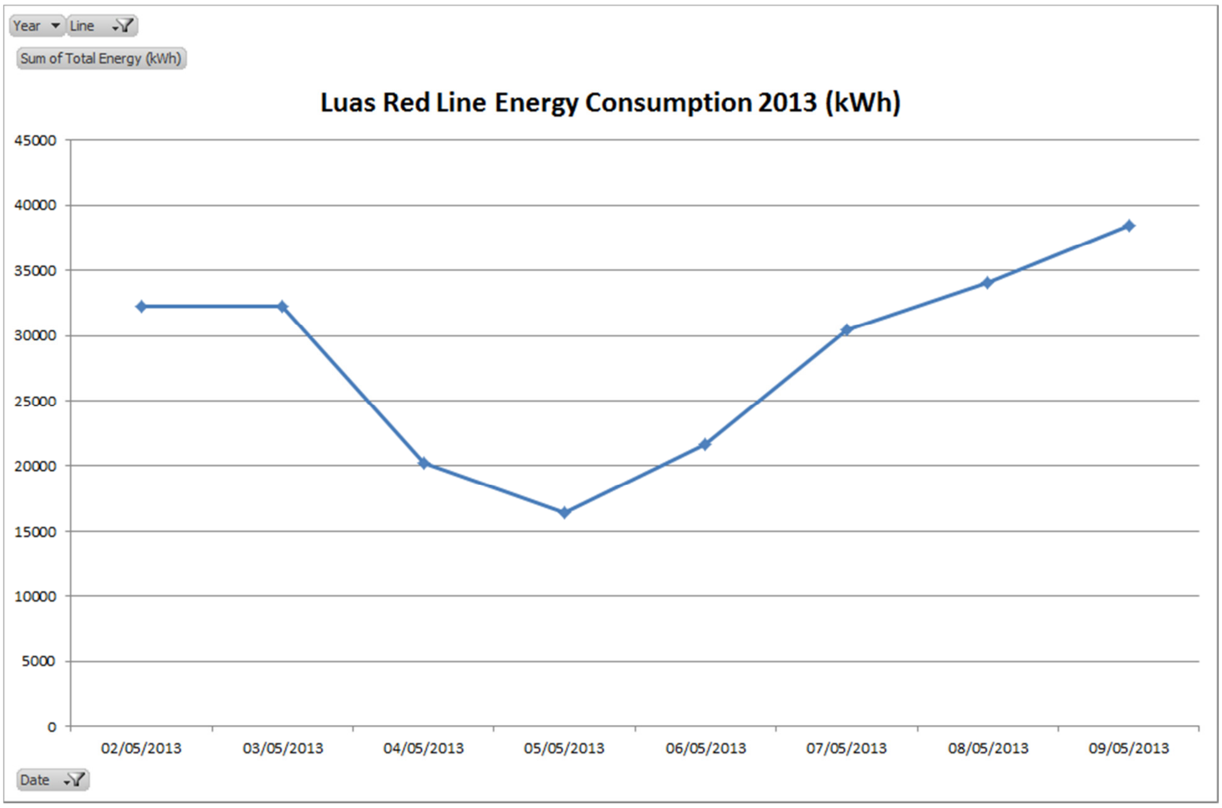


Figure 72: Luas Red Line Daily Energy Consumption 2013

4.3.3 Climatic Influences

The climate and in particular air temperature has a significant and disproportional impact on Luas energy consumption. The foremost reason for this is the passenger heating and ventilation systems which are fitted to Luas vehicles. As discussed in previous chapters, the maximum consumption of the Luas heating and ventilation system is 60 kWh per tram [104]. Once trams are prepped the heating and ventilation system is activated, with the energy consumption dependant on the external temperature. This is the case for all trams, including those operating in passenger service and trams prepped within the depots. If the external air temperature drops below 4°C, the heating and ventilation systems operate in full heating mode, consuming 60 kWh per tram. With a maximum number of trams of 50 in passenger service at one time and the potential for a further 16 to be prepped in each depot the energy consumption of the Luas system increases dramatically in cold weather. During extreme weather conditions with prolonged periods where the air temperature is below 0°C there is a risk of ice build-up on the OCS, both within the depot and on the main line. In these situations mitigating actions to keep trams prepped may be taken by the operations department. This results in a constant current being drawn through the OCS by the prepped trams to keep the OCS ice free. Such decisions are required to ensure a reliable tram service for traveling passengers however these decisions come at the expense of dramatically increased energy consumption.

From Figure 73 it is clear to see the trend in energy consumption throughout the year. During winter month's energy consumption can be up to 50% more compared with summer months on the Red Line [100].

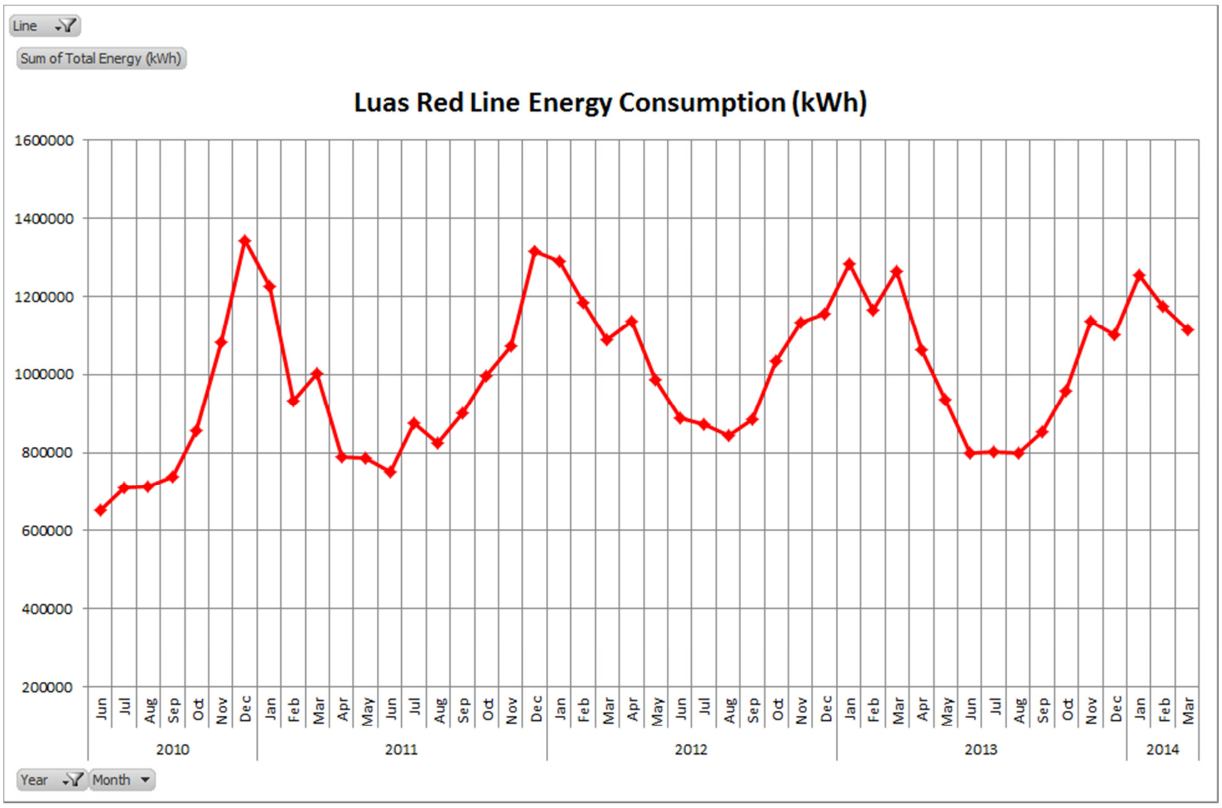


Figure 73: Luas Red Line Energy Consumption

A similar trend can be seen on the Green line in Figure 74, however the percentage difference between summer and winter months energy consumption is less. This is due to the fact that less tram vehicles and passenger services are operated on the Luas Green Line.

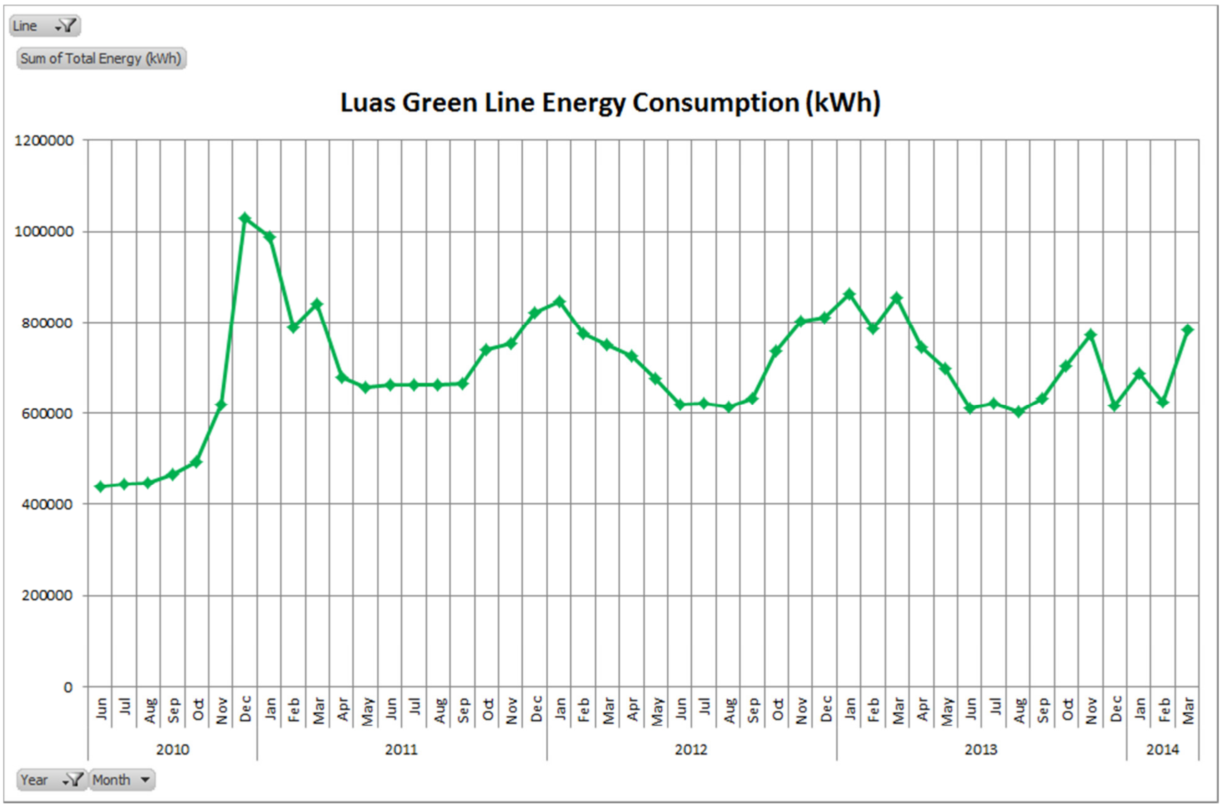


Figure 74: Luas Green Line Energy Consumption

Chapter 5: *Energy Reduction Proposals*

5.1 Rolling Stock

The energy reduction initiatives identified in relation to Luas rolling stock are detailed in this section.

5.1.1 Replacement of Traction Motors

The motor bogies including the wheel-sets and traction motors of the Luas 401 and 402 trams were designed and manufactured by Alstom over 10 years ago. At that time they were designed for reliability, maintainability and efficiency using the best technologies available. Luas was only the second operation in the world to take delivery of the Alstom manufactured Citadis 401 fleet, Orleans in France being the first. Each year Luas trams are maintained as per the annual maintenance plan (AMP) which is derived from the original engineer's manual. Trams undergo regular scheduled maintenance activities based on set kilometre intervals [109]. As per the AMP, Luas motor bogies require little intrusive maintenance in the early years of operation. The first scheduled overhaul of Luas motor bogies takes places at 300,000 km and includes the replacement of valves, thermostats, hydraulic hoses, motor brushes and hydraulic brake oils. The second scheduled motor bogie overhaul takes place at 450,000 km, this overhaul is more intrusive and includes dismounting of motor cooling units for overhaul, inspection of suspension rods, and replacement of wheel-set components. The third and most intrusive scheduled maintenance overhaul of the motor bogies of Luas trams is at 600,000 km. This overhaul includes the replacement of crucial bogie fixings such as couplings, bolts and electrical connections [110]. As per the original engineers manual the traction motors and wheel-sets are not due for replacement until 900,000 km or 15 years of operation [111]. The Luas 401 fleet of trams have been in passenger operation for just over nine years and have an average total km of 580,000 km [112]. As a result the tractions motors and wheel-sets are not due for replacement for some time. More efficient traction motors are available in the market at present. To change the traction motors on Luas trams, a complete re-design of the entire motor bogie would first have to take place. This would include the potential replacement of axles, axle shafts, gearings and wheel-sets. The maintenance manual encompassing the motor bogie would also have to be updated and significant testing would have to take place before trams could enter passenger service. As a result, at this stage in the operation of Luas it is not feasible to replace the tractions motors simply for energy reduction purposes. An opportunity may exist once Luas trams have reached 900,000 km or 15 years of operation and the traction motors are due for replacement as per the AMP. At this time further research would be required to assess the impact of upgrading the traction motors to a more efficient motor such as the Bombardier Flexx Urban 1000 traction motor [62]. Other options such as rolling stock modernisation could be procured when Luas trams have reached the 900,000 km milestone. Companies such as Alstom provide these services where major rolling stock components such as the motor bogies and traction motors are replaced as part of an overall tram modernisation to ultimately increase efficiency, reduce energy and maintenance costs [113].

5.1.2 Modifications of the Passenger Heating and Ventilation Systems

Due to the extensive testing conducted as part of this research it was identified that the Luas heating and ventilation systems consumes as much as 60% of the total power per tram vehicle, this is some four times its original design allowance [91]. Further analysis of the current operation of the system, and potential modifications to reduce this energy consumption were undertaken. An analysis of fleet operations indicated the hours of service operated by Luas as per the current timetable, these hours are detailed in Table 15 [89].

Table 15: Luas Operational Hours (OOS =Out of Service)

Green Line Operational Hours									
	In Service	Lay Over	Pull In / Out	Preperation	Total	Total OOS	% OOS to In-Service	Total No of Vehicles	Average Hours OOS per Vehicle
Weekday	189:21:00	34:13:00	06:14:00	07:20:00	237:08:00	47:47:00	25.2	19	2:30:54
Saturday	137:10:00	32:16:00	04:46:00	03:40:00	177:52:00	40:42:00	29.7	11	3:42:00
Sunday	101:02:00	22:46:00	04:38:00	02:40:00	131:06:00	30:04:00	29.8	8	3:45:30
Red Line Operational Hours									
	In Service	Lay Over	Pull In / Out	Preperation	Total	Total OOS	% OOS to In-Service	Total No of Vehicles	Average Hours OOS per Vehicle
Weekday	329:57:00	60:22:00	12:27:00	11:12:00	413:58:00	84:01:00	25.5	27	3:06:42
Saturday	137:10:00	32:16:00	04:46:00	03:40:00	177:52:00	40:42:00	29.7	21	1:56:17
Sunday	185:09:00	52:41:00	08:28:00	06:49:00	253:07:00	67:58:00	36.7	17	3:59:53

Table Key;

i). "In-service" represents the actual hours the Luas fleet operates passenger service.

ii). "Lay Over" represents the total hours Luas vehicles spend idle at the end of line (shunt area), waiting to depart on the next service.

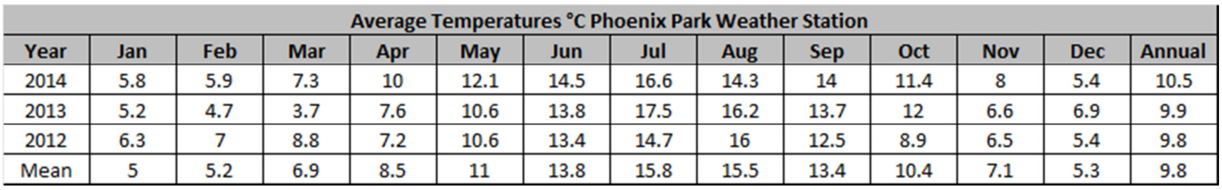
iii). "Pull In/Out" represents the time taken to exit the depot before going into passenger service and return to the depot post passenger service.

iv). "Preparation" represents the time taken by the driver to prepare tram vehicles, and complete pre-departure checks before departing for passenger service.

On weekday operations over both lines, 25% of the time Luas trams are in operation they are not in passenger service. During this time tram vehicles are fully prepped and functional and as a result the heating and ventilation systems are automatically activated (energy consumption will be temperature depending) [95]. During Saturday and Sunday operations, this non-passenger service time increases to almost 30% on the Red Line and 37% on the Green Line for Sunday operations. Table 15 also indicated the number of vehicles in operation during these periods, and the total number of out of service hours performed by each tram vehicle on both the Luas Red and Green lines.

Ireland’s maritime climate is influenced by the Atlantic Ocean and a polar front that exists around the country during winter months. Winters are cool and generally windy, summer months are mostly mild. According to the Irish Met office, the number of days with an air temperature below 0 °C in Dublin is 10 days per year and the average temperature is 10 °C. Table 16 details the monthly average temperatures for the Phoenix Park weather station, the most central weather station to the Luas Line for 2012, 2013 and 2014.

Table 16: Dublin Average Temperatures [114]



Average Temperatures °C Phoenix Park Weather Station

Year	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Annual
2014	5.8	5.9	7.3	10	12.1	14.5	16.6	14.3	14	11.4	8	5.4	10.5
2013	5.2	4.7	3.7	7.6	10.6	13.8	17.5	16.2	13.7	12	6.6	6.9	9.9
2012	6.3	7	8.8	7.2	10.6	13.4	14.7	16	12.5	8.9	6.5	5.4	9.8
Mean	5	5.2	6.9	8.5	11	13.8	15.8	15.5	13.4	10.4	7.1	5.3	9.8

Depending on external temperature conditions, the consumption of Luas heating and ventilation systems can differ greatly, from a minimum of 1 kW to a maximum of 60 kW [108]. Table 17 and 18 details the energy consumption of the heating and ventilation system during periods on non-passenger operations for 2012, established using daily temperature data from the Irish National Meteorological Service.

Table 17: Red Line Energy Heating and Ventilation Consumption

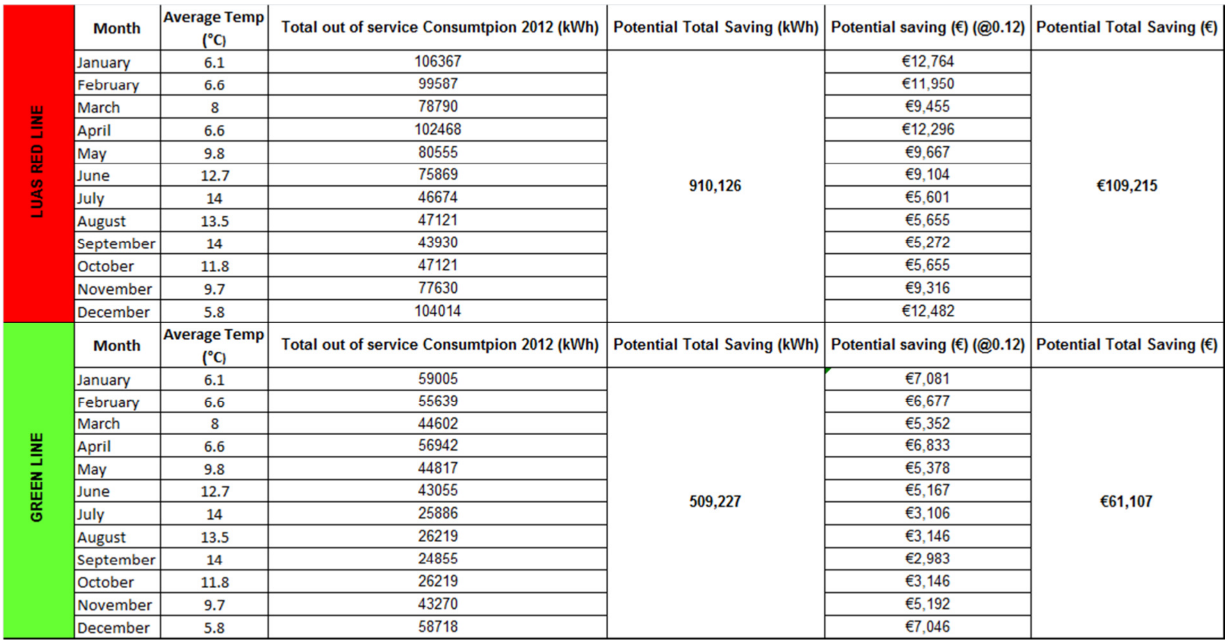
	Month	Average Temp (Oc)	Day	Heater Consumption (%)	Out of service (hours)	No of Vehicles	Average OOS Hours per Vehicle	Max H&V Consumption (kW)	Consumption per vehicle (kW)	TotalConsumption Per Fleet (kWh)	Days In Month	Total Monthly H&V Consumption (kWh)	Monthly Total (kWh)	Total Saving (kWh)
RED LINE	January	6.1	Weekday	70-90	84:01:00	27	03:06:42	59	47.2	3899	22	85778		910,126
	January	6.1	Saturday	70-90	40:42:00	21	01:56:17	59	47.2	1546	4	6184	106367	
	January	6.1	Sunday	70-90	67:58:00	17	03:59:53	59	47.2	2881	5	14405		
	February	6.6	Weekday	70-90	84:01:00	27	03:06:42	59	47.2	3899	21	81879		
	February	6.6	Saturday	70-90	40:42:00	21	01:56:17	59	47.2	1546	4	6184	99587	
	February	6.6	Sunday	70-90	67:58:00	17	03:59:53	59	47.2	2881	4	11524		
	March	8	Weekday	50-70	84:01:00	27	03:06:42	59	35.4	2925	22	64350		
	March	8	Saturday	50-70	40:42:00	21	01:56:17	59	35.4	1160	5	5800	78790	
	March	8	Sunday	50-70	67:58:00	17	03:59:53	59	35.4	2160	4	8640		
	April	6.6	Weekday	70-90	84:01:00	27	03:06:42	59	47.2	3899	21	81879		
	April	6.6	Saturday	70-90	40:42:00	21	01:56:17	59	47.2	1546	4	6184	102468	
	April	6.6	Sunday	70-90	67:58:00	17	03:59:53	59	47.2	2881	5	14405		
	May	9.8	Weekday	50-70	84:01:00	27	03:06:42	59	35.4	2925	23	67275		
	May	9.8	Saturday	50-70	40:42:00	21	01:56:17	59	35.4	1160	4	4640	80555	
	May	9.8	Sunday	50-70	67:58:00	17	03:59:53	59	35.4	2160	4	8640		
	June	12.7	Weekday	50-70	84:01:00	27	03:06:42	59	35.4	2925	21	61425		
	June	12.7	Saturday	50-70	40:42:00	21	01:56:17	59	35.4	1160	5	5800	75869	
	June	12.7	Sunday	50-70	67:58:00	17	03:59:53	59	35.4	2161	4	8644		
	July	14	Weekday	20-50	84:01:00	27	03:06:42	59	20.7	1711	22	37642		
	July	14	Saturday	20-50	40:42:00	21	01:56:17	59	20.7	678	4	2712	46674	
	July	14	Sunday	20-50	67:58:00	17	03:59:53	59	20.7	1264	5	6320		
	August	13.5	Weekday	20-50	84:01:00	27	03:06:42	59	20.7	1711	23	39353		
	August	13.5	Saturday	20-50	40:42:00	21	01:56:17	59	20.7	678	4	2712	47121	
	August	13.5	Sunday	20-50	67:58:00	17	03:59:53	59	20.7	1264	4	5056		
	September	14	Weekday	20-50	84:01:00	27	03:06:42	59	20.7	1711	20	34220		
	September	14	Saturday	20-50	40:42:00	21	01:56:17	59	20.7	678	5	3390	43930	
	September	14	Sunday	20-50	67:58:00	17	03:59:53	59	20.7	1264	5	6320		
	October	11.8	Weekday	20-50	84:01:00	27	03:06:42	59	20.7	1711	23	39353		
	October	11.8	Saturday	20-50	40:42:00	21	01:56:17	59	20.7	678	4	2712	47121	
	October	11.8	Sunday	20-50	67:58:00	17	03:59:53	59	20.7	1264	4	5056		
	November	9.7	Weekday	50-70	84:01:00	27	03:06:42	59	35.4	2925	22	64350		
	November	9.7	Saturday	50-70	40:42:00	21	01:56:17	59	35.4	1160	4	4640	77630	
	November	9.7	Sunday	50-70	67:58:00	17	03:59:53	59	35.4	2160	4	8640		
	December	5.8	Weekday	70-90	84:01:00	27	03:06:42	59	47.2	3899	21	81879		
	December	5.8	Saturday	70-90	40:42:00	21	01:56:17	59	47.2	1546	5	7730	104014	
	December	5.8	Sunday	70-90	67:58:00	17	03:59:53	59	47.2	2881	5	14405		

Table 18: Green line Energy Heating and Ventilation Consumption

	Month	Average Temp (O_c)	Day	Heater Consumption (%)	Out of service hours	No of Vehicles	Average OOS Hours per Vehicle	Max H&V Consumption (kW)	Consumption per vehicle (kW)	TotalConsumption Per Fleet (kWh)	Days In Month	Total Monthly H&V Consumption (kWh)	Monthly Total (kWh)	Total Saving (kWh)
GREEN LINE	January	6.1	Weekday	70-90	47:47:00	19	2:30:54	59	47.2	2063	22	45386		509,227
	January	6.1	Saturday	70-90	40:42:00	11	3:42:00	59	47.2	1776	4	7104	59005	
	January	6.1	Sunday	70-90	30:04:00	8	3:45:30	59	47.2	1303	5	6515		
	February	6.6	Weekday	70-90	47:47:00	19	2:30:54	59	47.2	2063	21	43323		
	February	6.6	Saturday	70-90	40:42:00	11	3:42:00	59	47.2	1776	4	7104	55639	
	February	6.6	Sunday	70-90	30:04:00	8	3:45:30	59	47.2	1303	4	5212		
	March	8	Weekday	50-70	47:47:00	19	2:30:54	59	35.4	1547	22	34034		
	March	8	Saturday	50-70	40:42:00	11	3:42:00	59	35.4	1332	5	6660	44602	
	March	8	Sunday	50-70	30:04:00	8	3:45:30	59	35.4	977	4	3908		
	April	6.6	Weekday	70-90	47:47:00	19	2:30:54	59	47.2	2063	21	43323		
	April	6.6	Saturday	70-90	40:42:00	11	3:42:00	59	47.2	1776	4	7104	56942	
	April	6.6	Sunday	70-90	30:04:00	8	3:45:30	59	47.2	1303	5	6515		
	May	9.8	Weekday	50-70	47:47:00	19	2:30:54	59	35.4	1547	23	35581		
	May	9.8	Saturday	50-70	40:42:00	11	3:42:00	59	35.4	1332	4	5328	44817	
	May	9.8	Sunday	50-70	30:04:00	8	3:45:30	59	35.4	977	4	3908		
	June	12.7	Weekday	50-70	47:47:00	19	2:30:54	59	35.4	1547	21	32487		
	June	12.7	Saturday	50-70	40:42:00	11	3:42:00	59	35.4	1332	5	6660	43055	
	June	12.7	Sunday	50-70	30:04:00	8	3:45:30	59	35.4	977	4	3908		
	July	14	Weekday	20-50	47:47:00	19	2:30:54	59	20.7	905	22	19910		
	July	14	Saturday	20-50	40:42:00	11	3:42:00	59	20.7	779	4	3116	25886	
	July	14	Sunday	20-50	30:04:00	8	3:45:30	59	20.7	572	5	2860		
	August	13.5	Weekday	20-50	47:47:00	19	2:30:54	59	20.7	905	23	20815		
	August	13.5	Saturday	20-50	40:42:00	11	3:42:00	59	20.7	779	4	3116	26219	
	August	13.5	Sunday	20-50	30:04:00	8	3:45:30	59	20.7	572	4	2288		
	September	14	Weekday	20-50	47:47:00	19	2:30:54	59	20.7	905	20	18100		
	September	14	Saturday	20-50	40:42:00	11	3:42:00	59	20.7	779	5	3895	24855	
	September	14	Sunday	20-50	30:04:00	8	3:45:30	59	20.7	572	5	2860		
	October	11.8	Weekday	20-50	47:47:00	19	2:30:54	59	20.7	905	23	20815		
	October	11.8	Saturday	20-50	40:42:00	11	3:42:00	59	20.7	779	4	3116	26219	
	October	11.8	Sunday	20-50	30:04:00	8	3:45:30	59	20.7	572	4	2288		
	November	9.7	Weekday	50-70	47:47:00	19	2:30:54	59	35.4	1547	22	34034		
	November	9.7	Saturday	50-70	40:42:00	11	3:42:00	59	35.4	1332	4	5328	43270	
	November	9.7	Sunday	50-70	30:04:00	8	3:45:30	59	35.4	977	4	3908		
	December	5.8	Weekday	70-90	47:47:00	19	2:30:54	59	47.2	2063	21	43323		
	December	5.8	Saturday	70-90	40:42:00	11	3:42:00	59	47.2	1776	5	8880	58718	
	December	5.8	Sunday	70-90	30:04:00	8	3:45:30	59	47.2	1303	5	6515		

There are a number of potential modifications, which will result in the reduction of energy consumption associated with the Luas heating and ventilation system. Based on the results outlined in Tables 15 and 16, this research proposes design modifications that would automatically disable the heating and ventilation system during periods of non-passenger operations. These modifications would result in vast energy savings, while not adversely affecting the operation of the heating and ventilation system while passengers are on-board. These modifications have the potential to save an estimated 910,000 kWh on the Red Line and 509,000 kWh on the Green Line, based on the average industry standard unit price for electricity this would result in a saving of €179,000 in one year. An academic paper was published and presented at the Irish Transport Research Network conference in Trinity College in 2013 and can be seen in appendix one of this thesis. The modifications were also shortlisted for an award at the 2013 Sustainable Energy Authority of Ireland Energy awards. Table 19 details the breakdown of energy savings per month across both Luas lines [108].

Table 19: Potential Energy Savings



	Month	Average Temp (°C)	Total out of service Consumtpion 2012 (kWh)	Potential Total Saving (kWh)	Potential saving (€) (@0.12)	Potential Total Saving (€)
LUAS RED LINE	January	6.1	106367	910,126	€12,764	€109,215
	February	6.6	99587		€11,950	
	March	8	78790		€9,455	
	April	6.6	102468		€12,296	
	May	9.8	80555		€9,667	
	June	12.7	75869		€9,104	
	July	14	46674		€5,601	
	August	13.5	47121		€5,655	
	September	14	43930		€5,272	
	October	11.8	47121		€5,655	
	November	9.7	77630		€9,316	
	December	5.8	104014		€12,482	
GREEN LINE	Month	Average Temp (°C)	Total out of service Consumtpion 2012 (kWh)	Potential Total Saving (kWh)	Potential saving (€) (@0.12)	Potential Total Saving (€)
	January	6.1	59005	509,227	€7,081	€61,107
	February	6.6	55639		€6,677	
	March	8	44602		€5,352	
	April	6.6	56942		€6,833	
	May	9.8	44817		€5,378	
	June	12.7	43055		€5,167	
	July	14	25886		€3,106	
	August	13.5	26219		€3,146	
	September	14	24855		€2,983	
	October	11.8	26219		€3,146	
	November	9.7	43270		€5,192	
	December	5.8	58718		€7,046	

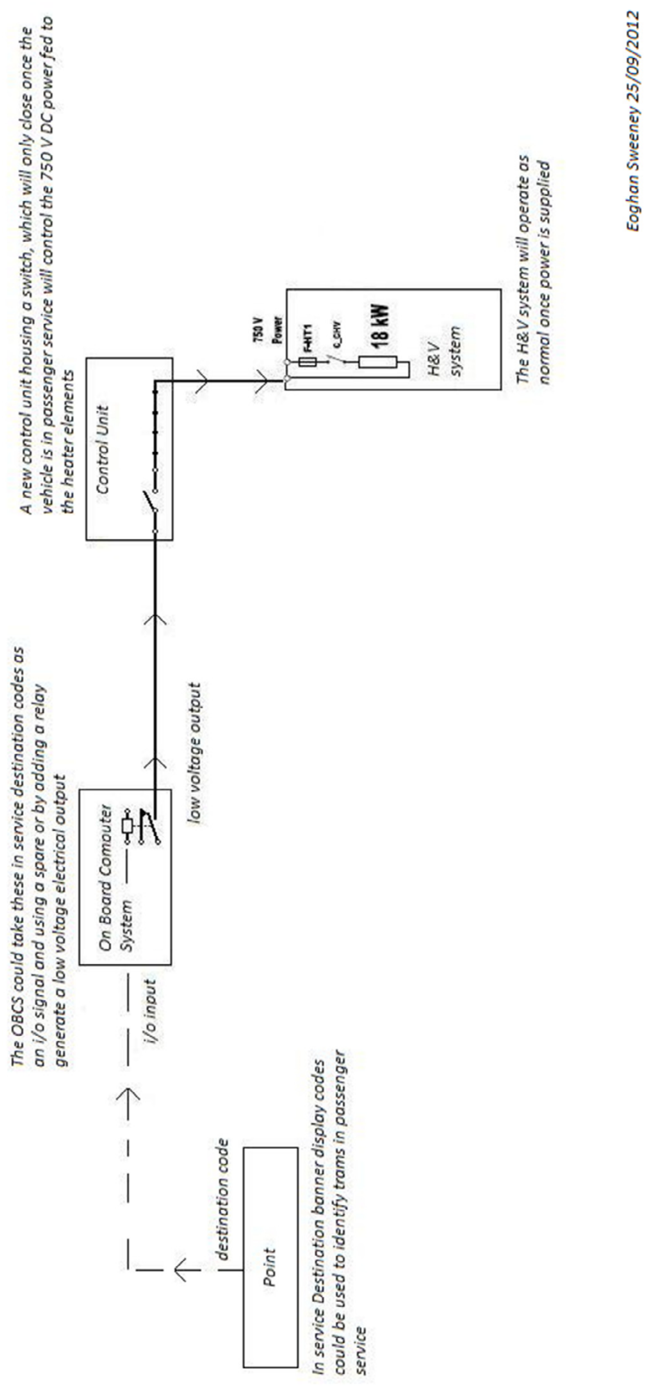
This research proposed two modifications to automatically disable the heating and ventilation system during periods of non-passenger operations, and a third modification has also been identified to increase the efficiency of the system while in operation by reducing the set point temperature profile of the heating and ventilation system. Modifications to disable the heating and ventilation system have the potential to save in the region of 1,419,353 kWh per year. This is an average figure calculated over a twelve month period. Savings would realistically be greater in winter months and less during summer periods as detailed in Table 19.

5.1.2.1 Disabling the heating and ventilation system while operating in periods of non-passenger service (when in traction).

The first modification proposed involves disabling the heating and ventilation system while operating in periods of non-passenger service, but where the tram is in traction. In order to achieve this, a number of options were explored. The following modification has been identified through this research as the most simplistic, resulting in the least required modification to Luas vehicles.

The modification process is as follows, passenger service vehicles automatically display a set destination on the external display banner. This is achieved through the AVLS which uses specific service files to determine what service a vehicle is operating and where its destination is. Ground loops are located at regular intervals in the track bed. A transponder underneath the driving cab of each tram recognises each ground loop through an electrical signal. Using these ground loops the AVLS can detect when a vehicle is at the designated stop to begin passenger service. Once this loop is detected by the AVLS the external display will automatically display the vehicles destination. Each destination display will have a unique coding within the service file [115]. This coding can be used to determine when a vehicle enters passenger service. Each unique coding can be flagged within the service file. Once a flag is identified an input/output signal will be generated and sent to the vehicles on-board computer system (OBCS). This connection and communication is already in place on Luas vehicles for other functions and therefore will only require modification to accommodate this new process. The OBCS will take this input/output signal once the vehicle enters service and the destinations are displayed, and by adding a new relay generate a low voltage electrical output. This output will then be hard wired to a new control unit within the heating and ventilation system. Within this new control unit will be an on/off switch. On command the switch will close supplying power to the heating and ventilation system once the tram is in passenger service. The system will then work as originally designed based on the set point formula. Once the tram completes passenger service the AVLS will automatically revert back to “not in-service”, the switch within the new control unit will then open disconnecting power to the system.

This modification would result in no power being supplied to the heating and ventilation system when the tram is not in passenger service. These times equate to 77 hours per week across both lines [89]. Figure 75 shows the modification in schematic form.



In service Destination banner display codes could be used to identify trams in passenger service

The OBCS could take these in service destination codes as an i/o signal and using a spare or by adding a relay generate a low voltage electrical output

A new control unit housing a switch, which will only close once the vehicle is in passenger service will control the 750 V DC power fed to the heater elements

The H&V system will operate as normal once power is supplied

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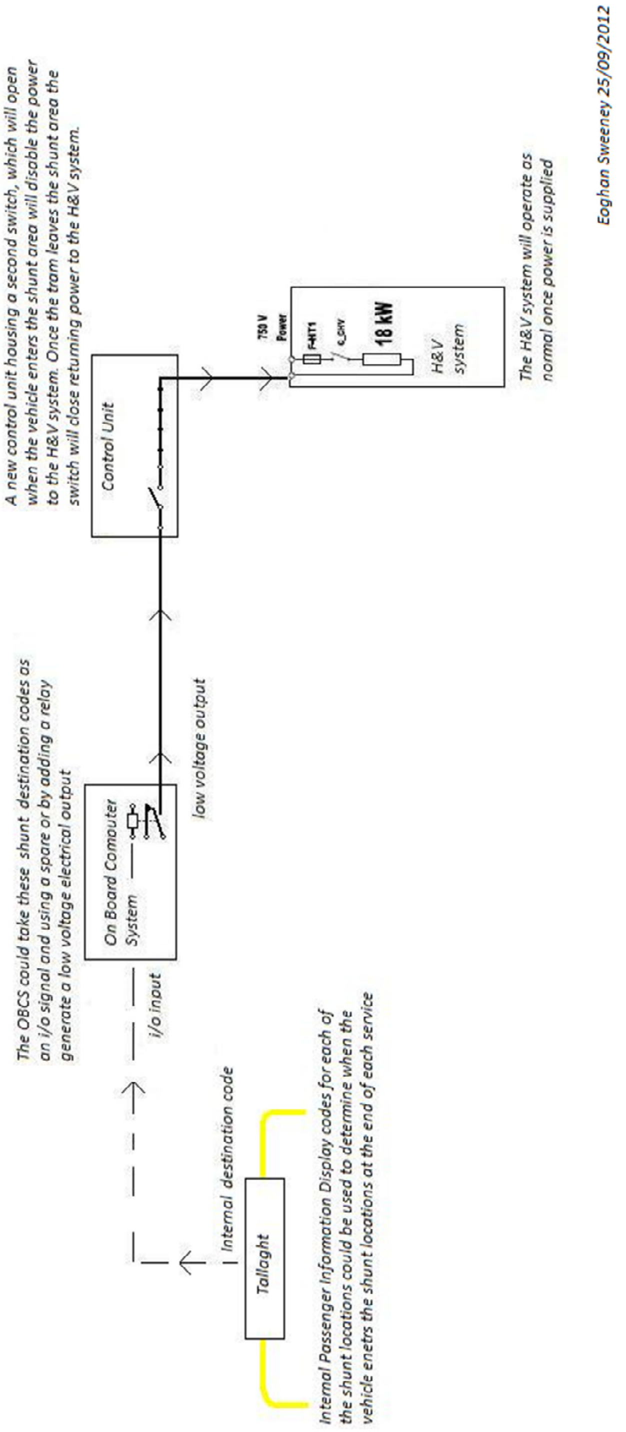
Figure 75: Heating and Ventilation Modification A Schematic

The shunt is the area at the end of each line. Vehicles can spend anywhere from 5-20 minutes in the shunt waiting to depart on their next service as per the timetable [89]. While vehicles are in the shunt, the tram is prepped (switched on) and effectively in-service. As a result, the AVLS destination displays are activated and therefore, this modification will not disable the heating and ventilation system during these periods. A second modification has been proposed for shunt locations.

5.1.2.2 Disabling the heating and ventilation system while stable in the shunt.

The modification process is as follows. The automatic vehicle location system communicates with ground loops located throughout the Luas system inside the track bed. Once a vehicle passes over these loops the AVLS can locate the vehicle anywhere on the line based on loop identifications. Using this system, the destination each vehicle is about to enter is identified by the AVLS and the destination name is displayed on the internal passenger displays for information. Each destination display will have a unique coding within the service file [115]. This coding can be used to determine when a vehicle enters the shunt locations. Each unique coding for all the six shunt locations across both Luas Red and Green Lines can be flagged within the service file. Once the flag is identified an input/output signal will be generated and sent to the vehicles OBCS similar to the previously detailed modification. This connection and communication is already in place on Luas vehicles and therefore will only have to be modified to accommodate this new process. The OBCS will take this input/output signal once the vehicle enters the shunt locations. By adding a new relay to the OBCS, a low voltage electrical output will be generated. This output will be hard wired to the new control unit previously detailed in section A. Within this new control unit will be a second switch, located after the first switch, in-series. On command the switch will open disconnecting power to the heating and ventilation system. The system will not be supplied power while in the shunt locations. Once the vehicle leaves the shunt locations the AVLS, through ground loops will recognise the vehicle has left and the switch will close again, supplying power back to the heating and ventilation system. This modification would result in no power being supplied to the system while stable in the shunt areas awaiting the next departure. These periods equate to 234 hours per week across both lines [89]. Figure 76 shows the modification in schematic form.



A new control unit housing a second switch, which will open when the vehicle enters the shunt area will disable the power to the H&V system. Once the tram leaves the shunt area the switch will close returning power to the H&V system.

The H&V system will operate as normal once power is supplied

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The OBCS could take these shunt destination codes as an i/o signal and using a spare or by adding a relay generate a low voltage electrical output

Internal Passenger Information Display codes for each of the shunt locations could be used to determine when the vehicle enetrs the shunt locations at the end of each service

Figure 76: Heating and Ventilation Modification B Schematic

These modifications are based on harvesting existing systems installed on Luas vehicles. This will result in the least intrusive modifications to Luas trams. The majority of the work involved in these modifications is the manipulation of the AVLS system to identify specific ground loops. This is a software modification and can be achieved off site and simply uploaded to each tram. The only intrusive work which must take place on each vehicle is the installation of an additional two relays in the OBCS, the wiring between the OBCS and the heating and ventilation system and the installation of a two switch control unit. It should also be noted that these modifications disable the current to the resistor heaters only and not the ventilation fan. Ventilation must be maintained at all times within the passenger saloon to control the regulation of the fresh air supply.

5.1.2.3 Reducing the set point temperature profile of the heating and ventilation system.

The original set point profile for the Luas heating and ventilation systems resulted in the system endeavouring to reach an internal temperature of at least 12°C [95]. From tests conducted as part of this research it was identified that during winter operations the heating and ventilation system fails to reach the set point as a result of poor insulation and regular door openings. As a consequence the system was in heating mode 100% of the time once the external temperature drops below 4°C. Therefore the set point profile was evaluated to be inefficient for Luas operations. In order to reduce the energy consumption associated with the system, the set point formula could be modified to reduce the period of time the system is activated and heating.

The modification process is as follows. The set point profile for Luas heating and ventilation system is determined by a fluid formula, which incorporates the external temperature. The formula is 20 C + 0.25 X (STN – 17ºC), where STN is the temperature of the air at the inlet. This formula is set within the control unit of the heating and ventilation system and can be simply modified by connecting into the control unit at source [95]. By modifying this formula to 20ºC + 0.25 x (STN – **50ºC**) a more realistic and efficient set point profile is achieved. The energy consumption associated with the system will be reduce, as the period of time the system is activated in full heating mode will be reduce. Note that the 3 functional setting to which the system operates as detailed in section 4.1.3 of chapter four will remain as designed. Prior to testing, it was difficult to quantify or estimate the saving such a modification would achieve. As each Luas vehicle operates at different times of the day with different passenger loads and ever changing external temperatures the savings would differ greatly from vehicle to vehicle and from day to day. Although it is difficult to estimate the energy savings, this modification will reduce the amount of time the system is on full heating mode, as the internal temperature will be achieved in a shorter time span. Future papers will detail the exact energy saving values achieved as a result of this modification. Figure 77 illustrates the proposed new set point profile.

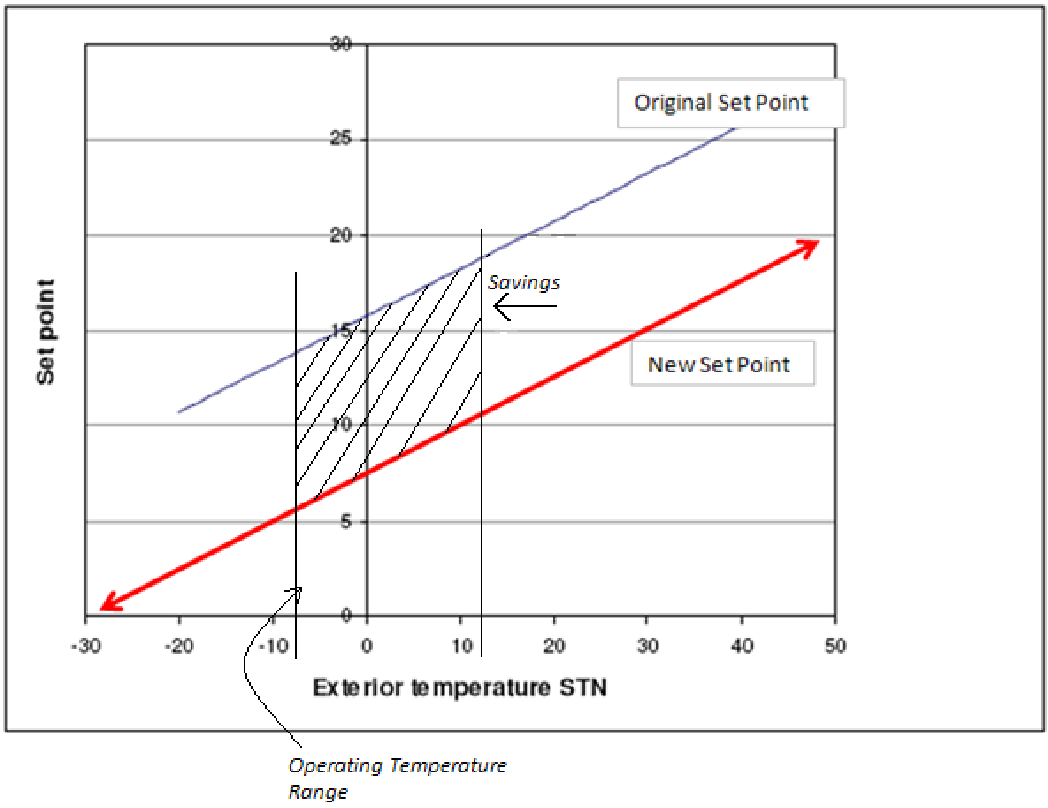


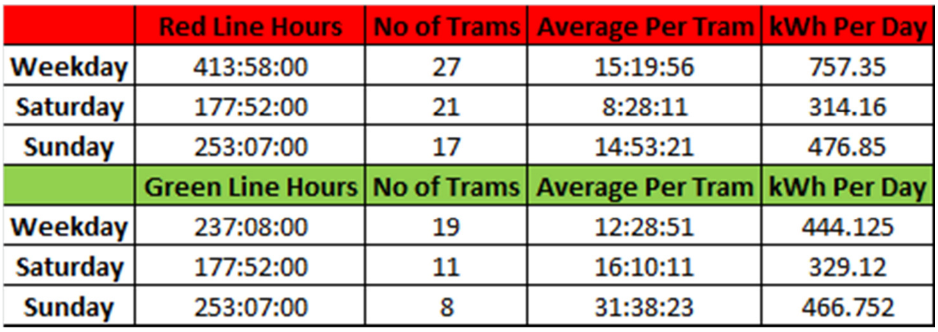
Figure 77: Proposed Set Point Formula Modification

Luas heating and ventilation systems can consume in excess of 60% of vehicle power in winter months, this is four times its designed power allowance. In some tests during this research, the consumption of the heating and ventilation system was in fact greater than that of the vehicles traction motors. Further analysis of Luas operations revealed the inefficient operation of the system. A conservative estimation found that some 1,629,353 kWh of energy could potentially be saved by adopting these 3 modifications. The modifications have been recommended to the research partners for implementation. It is recommended to trial these modifications on one tram and record the energy consumption for a period of at least six months incorporating the winter seasons to verify the results before implementation.

5.1.3 Replacement of Vehicle Lighting

The passenger compartment lighting of Luas vehicles consists of 52 X 36 W Philips T8 fluorescent tubes [97]. The operational safety recommendations for the Luas states that the interior passenger saloon lights should be permanently switched on while trams are in normal passenger service, from the driving cab. This results in total energy consumption for the interior lighting of 1.87 kW. Based on fleet operations [89] and the number of vehicles in operation, the average total energy consumption of the interior lighting of Luas vehicles on the Red line is 4,575 kWh per week, and 3,015 kWh on the Green Line. Table 20 details the breakdown of this calculation.

Table 20: Luas Tram Lighting Hours



	Red Line Hours	No of Trams	Average Per Tram	kWh Per Day
Weekday	413:58:00	27	15:19:56	757.35
Saturday	177:52:00	21	8:28:11	314.16
Sunday	253:07:00	17	14:53:21	476.85
	Green Line Hours	**No of Trams**	**Average Per Tram**	**kWh Per Day**
Weekday	237:08:00	19	12:28:51	444.125
Saturday	177:52:00	11	16:10:11	329.12
Sunday	253:07:00	8	31:38:23	466.752

The tram exterior lights include automatic activation of low beam headlights in the active driving cab and rear red marker lights which also act as brake lights. Marker lights located on the side of the vehicle are also activated once the vehicle is prepped. These light fittings, amount to a total of 260 W of power per tram vehicle. Should the high beams and indicator lights be switched on the power is 586 W [97]. High beams would rarely be activated on the Red Line due to the shared running track with regular on-coming vehicular traffic and the urban location which are sufficiently illuminated by public street lighting. The Green line has increased sections of completely segregated track where the high beams may be activated more often during night running. Due to the low wattage of the external lighting it is not desirable to replace the existing fittings with a more efficient fitting, simply for energy reduction purposes. However the external fittings could be replaced for a more efficient bulb such as an LED on a fail / replace strategy. LED bulbs could be replaced on a like for like basis and would require no modifications to existing lamp holders.

The interior lighting of Luas vehicles operate in accordance with EN 13272:2001 “Railway applications, Electrical lighting for rolling stock in public transport systems” [116]. An opportunity exists to replace the existing internal lighting on Luas vehicles with a more efficient light fitting or bulb. LED fittings have been chosen as a potential replacement due to their tested reliability, increased life time and wide use across the transport sector in recent years. The existing fluorescent tube lighting is supplied power from the tram static converter, through the battery at a supply of 24 V DC [97]. A ballast connection at each light provides the desired 240 V AC voltage. As a result the option exists to use either of these supplies for the new light fitting. The proposed LED tubes should also fit into the existing lamp holders with only minor modifications required. Table 21 details the specification required for the lamp replacement.

Table 21: Luas Tram Light Specifications [117]

Lamp Type	Voltage	LED Chip Qty	Length	Power	Lumen	Efficiency	PF	Colour	Beam Angle	Cover
LED T8 Tube	24V DC 240 V AC	Min 324 Pcs	120cm	Max 16W	≈1550Lm	92lm/w	1	4000-5000k	120d	Clear

The Phillips manufactured Master Led tube GA 110 1200 mm 19 W 840 I ROT meets the specifications outlined in Table 19. These lamps operate on a 240 V supply and therefore can be simply installed as a “plug and play” part to Luas vehicles, where no modification is required to the existing wiring or lamp holder. The lamps are also manufactured with the CE marking and are "*Restriction of Hazardous Substances*" (RoHS) compliant which is a requirement for Luas rolling stock [91]. Being 19 W, replacing the original fluorescent fittings these LED lamps will result in a 48% energy reduction. This equates to saving of 2,196 kWh on the Red Line and 1447 kWh on the Green line per week. Based on the average industry standard unit price for electricity of €0.12 this is a saving across the system of €437 per week or €22,724 per annum. This proposed retro fit does not require any major modification to Luas vehicles as the fittings will fit in the existing holders and will work from the existing power supply. The annual energy saving as a result of replacing the existing interior Luas tram lighting with LED bulbs would be in the region of 189,436 kWh. The installation of LED bulbs will also reduce maintenance costs as the life period of these bulbs is 60% longer than the original fluorescent bulbs.

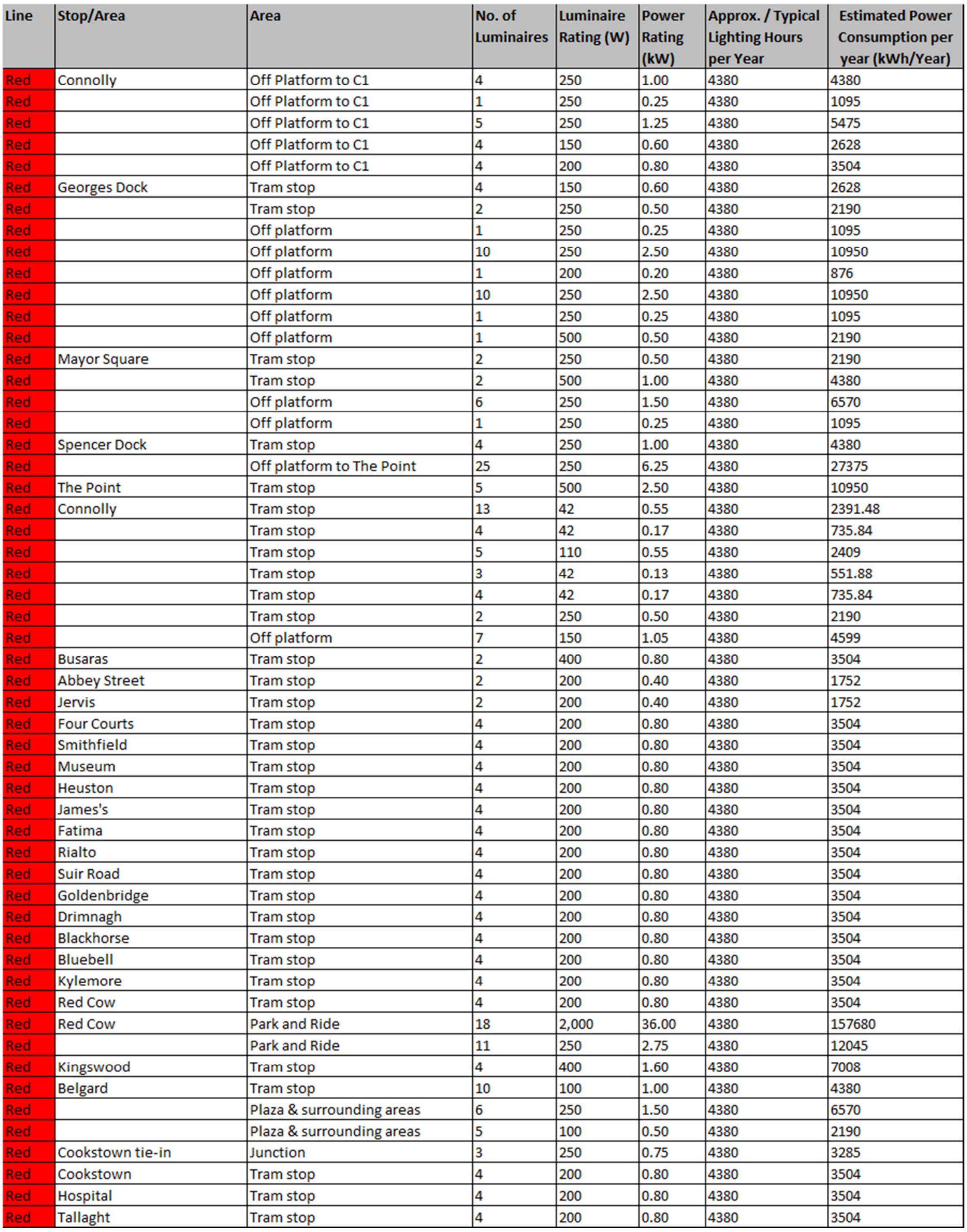
5.2 Infrastructure

Energy reduction proposals which influence Luas infrastructure are detailed in this section of the thesis.

5.2.1 Replacement of External Public Lighting

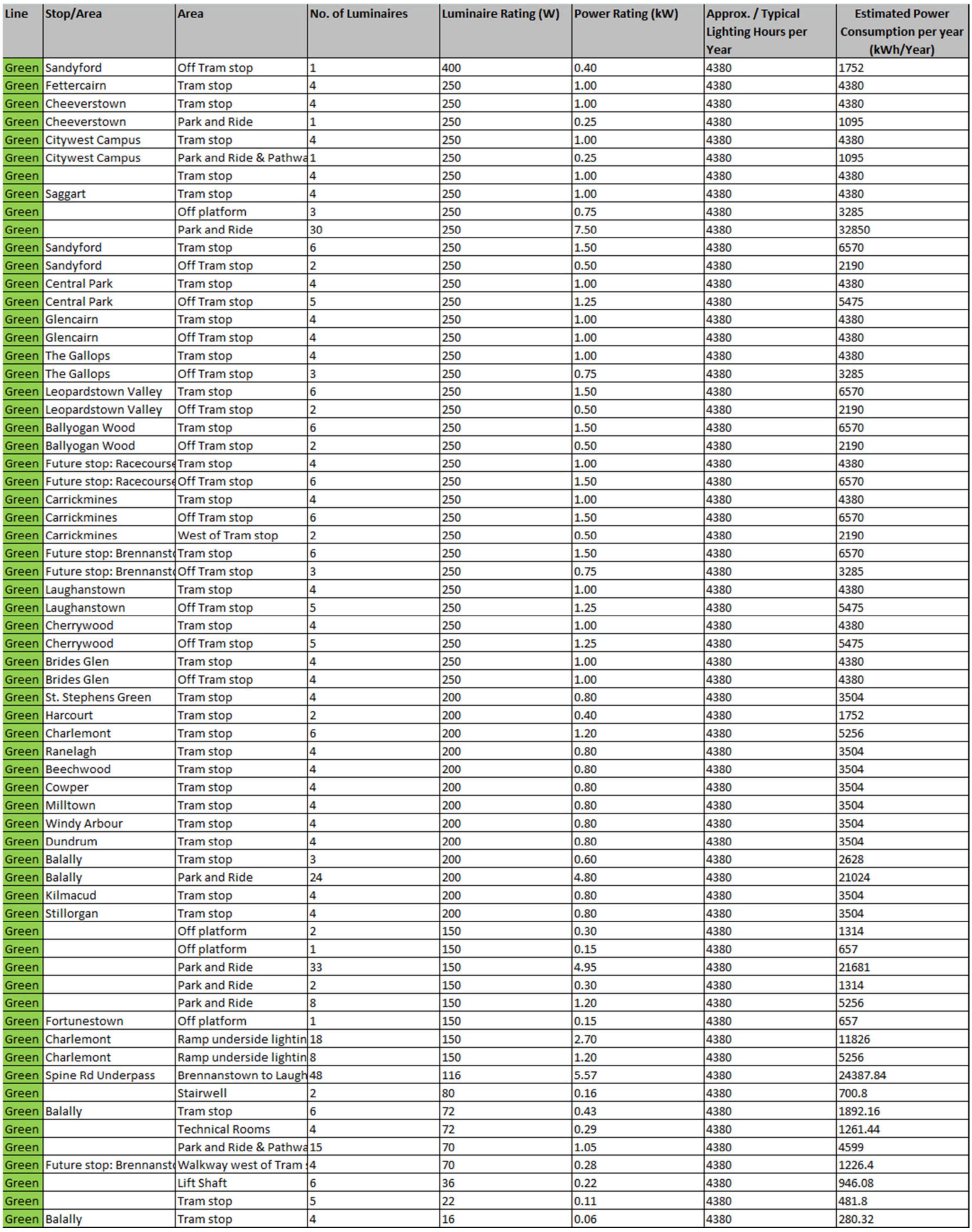
Luas infrastructure consists of an extensive area of track sections, platforms, car parks and two maintenance depots. With the exception of the maintenance depots and segregated section of track, Luas infrastructure is fully accessible to the public. As such, adequate public lighting must be supplied and maintained. Over 650 light fittings are installed throughout the Luas infrastructure. A survey conducted as part of this research identified the quantity and types of light fittings installed across the Luas infrastructure. The average lighting periods per year have also been calculated to determine the exact energy consumption of the light fittings of the Luas system. Table 22 details these light fittings on the Red line and Table 23 details the lights fittings identified on the Green line [118].

Table 22: Luas Red Line Lighting Loads



Line	Stop/Area	Area	No. of Luminaires	Luminaire Rating (W)	Power Rating (kW)	Approx. / Typical Lighting Hours per Year	Estimated Power Consumption per year (kWh/Year)
Red	Connolly	Off Platform to C1	4	250	1.00	4380	4380
Red		Off Platform to C1	1	250	0.25	4380	1095
Red		Off Platform to C1	5	250	1.25	4380	5475
Red		Off Platform to C1	4	150	0.60	4380	2628
Red		Off Platform to C1	4	200	0.80	4380	3504
Red	Georges Dock	Tram stop	4	150	0.60	4380	2628
Red		Tram stop	2	250	0.50	4380	2190
Red		Off platform	1	250	0.25	4380	1095
Red		Off platform	10	250	2.50	4380	10950
Red		Off platform	1	200	0.20	4380	876
Red		Off platform	10	250	2.50	4380	10950
Red		Off platform	1	250	0.25	4380	1095
Red		Off platform	1	500	0.50	4380	2190
Red	Mayor Square	Tram stop	2	250	0.50	4380	2190
Red		Tram stop	2	500	1.00	4380	4380
Red		Off platform	6	250	1.50	4380	6570
Red		Off platform	1	250	0.25	4380	1095
Red	Spencer Dock	Tram stop	4	250	1.00	4380	4380
Red		Off platform to The Point	25	250	6.25	4380	27375
Red	The Point	Tram stop	5	500	2.50	4380	10950
Red	Connolly	Tram stop	13	42	0.55	4380	2391.48
Red		Tram stop	4	42	0.17	4380	735.84
Red		Tram stop	5	110	0.55	4380	2409
Red		Tram stop	3	42	0.13	4380	551.88
Red		Tram stop	4	42	0.17	4380	735.84
Red		Tram stop	2	250	0.50	4380	2190
Red		Off platform	7	150	1.05	4380	4599
Red	Busaras	Tram stop	2	400	0.80	4380	3504
Red	Abbey Street	Tram stop	2	200	0.40	4380	1752
Red	Jervis	Tram stop	2	200	0.40	4380	1752
Red	Four Courts	Tram stop	4	200	0.80	4380	3504
Red	Smithfield	Tram stop	4	200	0.80	4380	3504
Red	Museum	Tram stop	4	200	0.80	4380	3504
Red	Heuston	Tram stop	4	200	0.80	4380	3504
Red	James's	Tram stop	4	200	0.80	4380	3504
Red	Fatima	Tram stop	4	200	0.80	4380	3504
Red	Rialto	Tram stop	4	200	0.80	4380	3504
Red	Suir Road	Tram stop	4	200	0.80	4380	3504
Red	Goldenbridge	Tram stop	4	200	0.80	4380	3504
Red	Drimnagh	Tram stop	4	200	0.80	4380	3504
Red	Blackhorse	Tram stop	4	200	0.80	4380	3504
Red	Bluebell	Tram stop	4	200	0.80	4380	3504
Red	Kylemore	Tram stop	4	200	0.80	4380	3504
Red	Red Cow	Tram stop	4	200	0.80	4380	3504
Red	Red Cow	Park and Ride	18	2,000	36.00	4380	157680
Red		Park and Ride	11	250	2.75	4380	12045
Red	Kingswood	Tram stop	4	400	1.60	4380	7008
Red	Belgard	Tram stop	10	100	1.00	4380	4380
Red		Plaza & surrounding areas	6	250	1.50	4380	6570
Red		Plaza & surrounding areas	5	100	0.50	4380	2190
Red	Cookstown tie-in	Junction	3	250	0.75	4380	3285
Red	Cookstown	Tram stop	4	200	0.80	4380	3504
Red	Hospital	Tram stop	4	200	0.80	4380	3504
Red	Tallaght	Tram stop	4	200	0.80	4380	3504

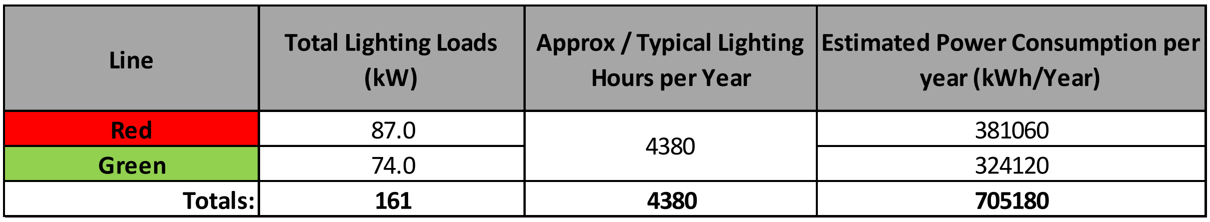
Table 23: Luas Green Line Lighting Loads



Line	Stop/Area	Area	No. of Luminaires	Luminaire Rating (W)	Power Rating (kW)	Approx. / Typical Lighting Hours per Year	Estimated Power Consumption per year (kWh/Year)
Green	Sandyford	Off Tram stop	1	400	0.40	4380	1752
Green	Fettercairn	Tram stop	4	250	1.00	4380	4380
Green	Cheeverstown	Tram stop	4	250	1.00	4380	4380
Green	Cheeverstown	Park and Ride	1	250	0.25	4380	1095
Green	Citywest Campus	Tram stop	4	250	1.00	4380	4380
Green	Citywest Campus	Park and Ride & Pathwa	1	250	0.25	4380	1095
Green		Tram stop	4	250	1.00	4380	4380
Green	Saggart	Tram stop	4	250	1.00	4380	4380
Green		Off platform	3	250	0.75	4380	3285
Green		Park and Ride	30	250	7.50	4380	32850
Green	Sandyford	Tram stop	6	250	1.50	4380	6570
Green	Sandyford	Off Tram stop	2	250	0.50	4380	2190
Green	Central Park	Tram stop	4	250	1.00	4380	4380
Green	Central Park	Off Tram stop	5	250	1.25	4380	5475
Green	Glencairn	Tram stop	4	250	1.00	4380	4380
Green	Glencairn	Off Tram stop	4	250	1.00	4380	4380
Green	The Gallops	Tram stop	4	250	1.00	4380	4380
Green	The Gallops	Off Tram stop	3	250	0.75	4380	3285
Green	Leopardstown Valley	Tram stop	6	250	1.50	4380	6570
Green	Leopardstown Valley	Off Tram stop	2	250	0.50	4380	2190
Green	Ballyogan Wood	Tram stop	6	250	1.50	4380	6570
Green	Ballyogan Wood	Off Tram stop	2	250	0.50	4380	2190
Green	Future stop: Racecours	Tram stop	4	250	1.00	4380	4380
Green	Future stop: Racecours	Off Tram stop	6	250	1.50	4380	6570
Green	Carrickmines	Tram stop	4	250	1.00	4380	4380
Green	Carrickmines	Off Tram stop	6	250	1.50	4380	6570
Green	Carrickmines	West of Tram stop	2	250	0.50	4380	2190
Green	Future stop: Brennanst	Tram stop	6	250	1.50	4380	6570
Green	Future stop: Brennanst	Off Tram stop	3	250	0.75	4380	3285
Green	Laughanstown	Tram stop	4	250	1.00	4380	4380
Green	Laughanstown	Off Tram stop	5	250	1.25	4380	5475
Green	Cherrywood	Tram stop	4	250	1.00	4380	4380
Green	Cherrywood	Off Tram stop	5	250	1.25	4380	5475
Green	Brides Glen	Tram stop	4	250	1.00	4380	4380
Green	Brides Glen	Off Tram stop	4	250	1.00	4380	4380
Green	St. Stephens Green	Tram stop	4	200	0.80	4380	3504
Green	Harcourt	Tram stop	2	200	0.40	4380	1752
Green	Charlemont	Tram stop	6	200	1.20	4380	5256
Green	Ranelagh	Tram stop	4	200	0.80	4380	3504
Green	Beechwood	Tram stop	4	200	0.80	4380	3504
Green	Cowper	Tram stop	4	200	0.80	4380	3504
Green	Milltown	Tram stop	4	200	0.80	4380	3504
Green	Windy Arbour	Tram stop	4	200	0.80	4380	3504
Green	Dundrum	Tram stop	4	200	0.80	4380	3504
Green	Balally	Tram stop	3	200	0.60	4380	2628
Green	Balally	Park and Ride	24	200	4.80	4380	21024
Green	Kilmacud	Tram stop	4	200	0.80	4380	3504
Green	Stillorgan	Tram stop	4	200	0.80	4380	3504
Green		Off platform	2	150	0.30	4380	1314
Green		Off platform	1	150	0.15	4380	657
Green		Park and Ride	33	150	4.95	4380	21681
Green		Park and Ride	2	150	0.30	4380	1314
Green		Park and Ride	8	150	1.20	4380	5256
Green	Fortunestown	Off platform	1	150	0.15	4380	657
Green	Charlemont	Ramp underside lightin	18	150	2.70	4380	11826
Green	Charlemont	Ramp underside lightin	8	150	1.20	4380	5256
Green	Spine Rd Underpass	Brennanstown to Laugh	48	116	5.57	4380	24387.84
Green		Stairwell	2	80	0.16	4380	700.8
Green	Balally	Tram stop	6	72	0.43	4380	1892.16
Green		Technical Rooms	4	72	0.29	4380	1261.44
Green		Park and Ride & Pathwa	15	70	1.05	4380	4599
Green	Future stop: Brennanst	Walkway west of Tram	4	70	0.28	4380	1226.4
Green		Lift Shaft	6	36	0.22	4380	946.08
Green		Tram stop	5	22	0.11	4380	481.8
Green	Balally	Tram stop	4	16	0.06	4380	280.32

Luas infrastructure was originally designed over a decade ago. At that time less importance was placed on energy efficient lighting systems, which is now standard practice in the design stage of all construction projects. Original architectural preferences would have been a significant factor in the original design stages of the external Luas lighting systems. As a result Luas lighting systems consume excessive amounts of energy and require regular intervention and maintenance. This research suggests there exists an opportunity to replace a significant proportion of the Luas infrastructure external light fittings with more efficient and reliable fittings, which would reduce the annual energy consumption significantly. The total Luas lighting load per line is estimated in Table 24 [118].

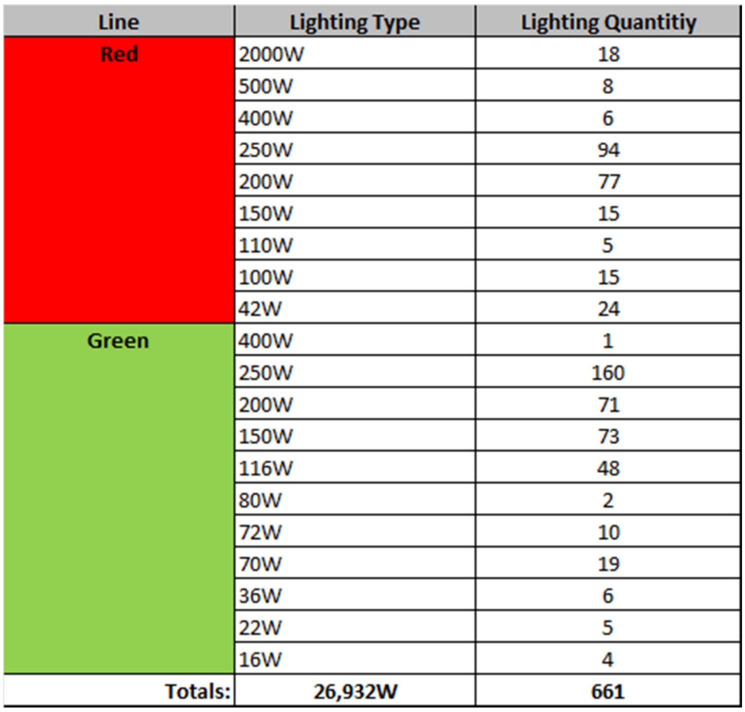
Table 24: Approximate Luas Lighting Loads



Line	Total Lighting Loads (kW)	Approx / Typical Lighting Hours per Year	Estimated Power Consumption per year (kWh/Year)
Red	87.0	4380	381060
Green	74.0		324120
Totals:	**161**	**4380**	**705180**

It would not be practical to replace every single light across the Luas system, therefore the emphasis was concentrated on the most prevalent and highest energy consuming light fittings of the Luas infrastructure. These fittings include the 2000 W, 500 W, 400 W and 250 W Metal Halide fittings which are installed on the platforms of all Luas stops. A breakdown of the number of the light fittings and their location is detailed in Table 25 [118].

Table 25: Luas Lighting Types and Quantities



Line	Lighting Type	Lighting Quantitiy
Red	2000W	18
	500W	8
	400W	6
	250W	94
	200W	77
	150W	15
	110W	5
	100W	15
	42W	24
Green	400W	1
	250W	160
	200W	71
	150W	73
	116W	48
	80W	2
	72W	10
	70W	19
	36W	6
	22W	5
	16W	4
Totals:	**26,932W**	**661**

In total across both the Red and Green Luas lines, there are over 435 light fittings which are greater than 200 W. The most prevalent of these fittings are the 250 W Metal Halide light fittings installed on the majority of Luas stops and at Luas car parks. Induction and LED lamps now offer a significantly more efficient option for lighting external public areas. Increased operational life, increased lux levels, and lower maintenance costs are also achieved when compared to Metal Halide lights. The light fittings installed in the public areas of Luas infrastructure are activated using day light sensors. On average each of the light fittings are activated for 12 hours per day. The total power of these 287 fittings over a one year period is 595,242 kWh [118].

It is proposed to replace the 500 W, 400 W, 250 W and 200 W Metal Halide lamps listed in Table 23 with either Induction or LED fittings. The 150 W and 100 W Metal Halide Neo Fittings can also be replaced with 100 W LED Neos's. A trial conducted as part of this research at Cookstown Luas stop on the Red Line took place during 2013. This trial involved the installation of four 163 W Disano 3270 LED fittings to replace the existing 250 W Metal Halide fittings. This LED fitting incorporated 72 individual LED bulbs. Figure 78 illustrates the colour rendering scale achieved from this trial. In the centre of the Luas Stop, an illuminance level of 81.27 Ix was achieved. This decreases towards the boundary edges of the platform, however a minimum illuminance of 25.09 Ix was maintained [119].

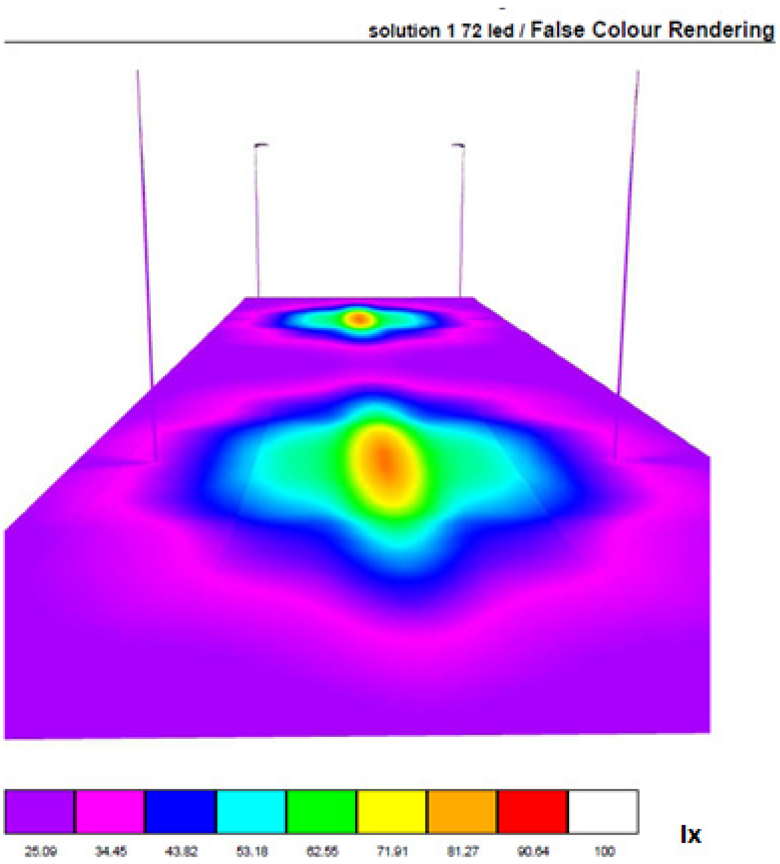


Figure 78: Cookstown Stop Colour Rendering Scale [119]

The retrofitting of LED light fittings at the Luas Cookstown stop represents a 35% saving compared with the Metal Halide fittings originally installed. Over a one year period the energy saving amounts to 1,525 kWh.

This type of retrofit programme could be applied to all Luas stops across the system and Luas car park sites. A choice of induction or LED lights can be installed to aid in the reduction of energy. For each site, considerations must be made regarding the required lux levels and appropriate electrical class of fitting. With the mass production of these new energy efficient light technologies such aspects can easily be accounted for.

In summary the retrofit of the most prevalent 500 W, 400 W, 250 W and 200 W Metal Halide lamps on the Luas infrastructure, would result in an average saving of 50% in energy consumption. This amounts to a 314,668 kWh saving per year. Maintenance down time would also be achieved as a result of such projects. Table 26 details the breakdown of the estimated energy savings.

Table 26: Potential Energy Savings

Line	Exiting Metal Halide Lighting	Lighting Quantity	Estimated Power Consumption per year (kWh/Year)	Replacement with LED	Lighting Quantity	Estimated Power Consumption per year (kWh)	Estimated Saving (kWh)
Red	2000W	18	157680	200W	18	15768	141912
	500W	8	17520	200W	8	7008	10512
	400W	6	10512	200W	6	4284	6228
	250W	94	102930	163W	94	67014	35916
	200W	77	67452	163W	77	54973	12479
Green	400W	1	1752	200W	1	714	1038
	250W	160	175200	163W	160	114230	60970
	200W	71	62196	163W	71	50677	11519
Total	-	435	595242	-	435	314668	280574

5.2.2 Replacement of Internal Depot Lighting

Both Luas depots incorporate large indoor workshops for maintenance of Luas vehicles. Both depots are significant in size and can cater for the simulatinious maintenance of up to 6 Luas trams. In order to safely preform maintenance tasks on Luas vehicles while in the workshop adequete lighting is required. When originally designed, Luas depot workshops were instlled with 400 W Metal Halide light fittings. After 10 years these fittings have become outdated, and those of which are nearing the end of their life have reduced lighting output levels. Metal Halide fittings also take a period of time to achieve their full lighting capacity and overheat when activated for long periods of time. This is not ideal for a workshop environment where instant light is required in certain areas. As maintenance work is on-going 24 hours a day, 364 days a year the lifetime of light fittings is also an important factor. This research has identified an opportunity to replace the Luas depot workshop light fittings. A trial as part of this research, included the replacement of 16 lights within the Red Cow depot in 2012. The 400 W Metal Halide fittings were replaced with 200 W Induction fittings. Comprehensive analysis took place of the area where the fittings were to be installed, to maximise the lux levels in the area [120]. Figure 79 details the colour rendering of this area known as the bogie overhaul section area of the workshop. An illuminance level of 500 Ix was achieved at 2 meters above ground. This is a significant increase on the Metal Halide fittings originally installed.

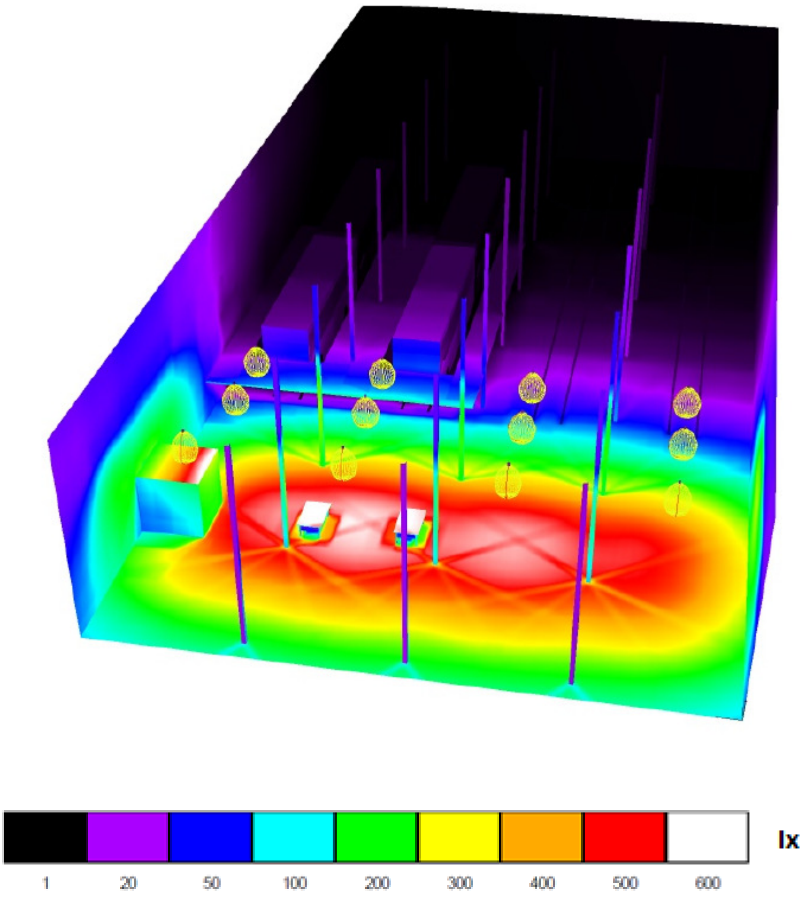


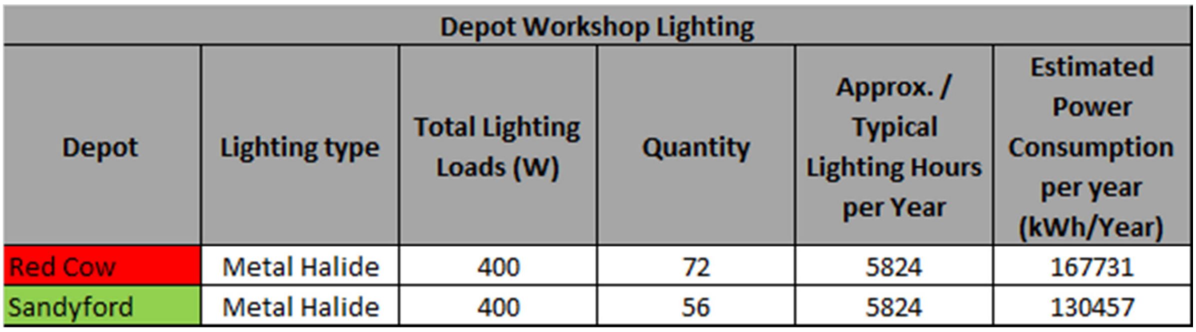
Figure 79: Red Cow Depot Colour Rendering Scale [120]

Once the fittings were installed the increased lux levels were evident. A trial in an Irish Rail depot was consulted before instalation at the Red Cow. The light emitted from the induction light fittings was visably brighter and clearer. Figure 80 shows the lighting achieved as part of this trial.

Figure 80: Red Cow Depot Workshop Lighting Trial

The trial at the Red Cow Depot achieved a 50% reduction in energy consumtpion using the 16 light fittings. This reducion was confirmd by a voltage test once the new Induction fittings were installed. The success of this trial has led to the recommendation by this reasearch to replace the remaining fitings across both Red and Sandyford Luas depots. Table 27 details the energy consumtpion associated with the original Metal Halide fittings. The anuual energy consumption over a one year period equates to 298,188 kWh.

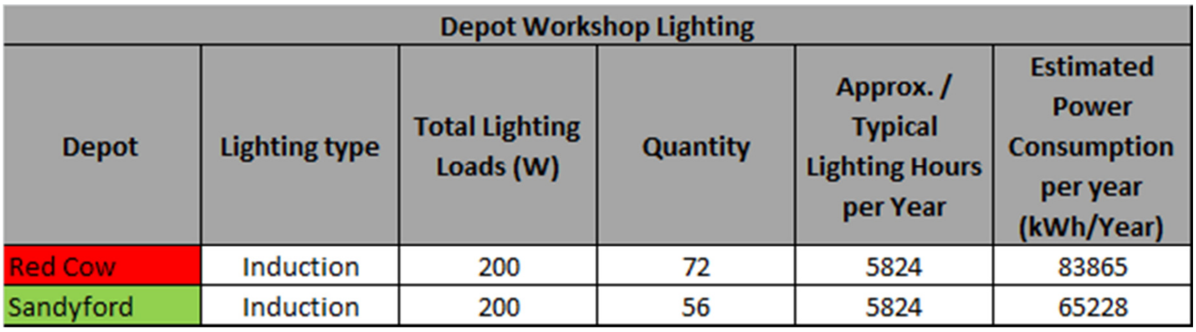
Table 27: Current Luas Depot Lighting



Depot Workshop Lighting					
Depot	Lighting type	Total Lighting Loads (W)	Quantity	Approx. / Typical Lighting Hours per Year	Estimated Power Consumption per year (kWh/Year)
Red Cow	Metal Halide	400	72	5824	167731
Sandyford	Metal Halide	400	56	5824	130457

Replacing these fittings with 200 W Induction fittings represents a 50% reduction in energy consumption, some 149,093 kWh per year as detailed in Table 28.

Table 28: Proposed Luas Depot Lighting



Depot Workshop Lighting					
Depot	Lighting type	Total Lighting Loads (W)	Quantity	Approx. / Typical Lighting Hours per Year	Estimated Power Consumption per year (kWh/Year)
Red Cow	Induction	200	72	5824	83865
Sandyford	Induction	200	56	5824	65228

5.2.3 Considerations for Renewable Energy Generation

As Luas is a significant energy user, an investment in sources of renewable energy generation would result in less dependence on energy supplied from the national grid. Due to the nature of Luas operations (energy demand is highest during peak times) and the reliability issues with sources of renewable energy it would not be envisaged that renewable energy would be the sole supplier of energy to the Luas network. However, renewable energy sources have the potential to provide an alternative, supplementary energy supply for the Luas system as a whole or for specific elements of the system such as the depots or stops. The two main sources of renewable energy applicable to Luas are wind energy and solar PV energy. Based on the experience of other LRT operations such as Infrabel in Belgium [42], investments in renewable energy projects can result in significant energy savings and reductions in CO_2 emissions.

The Luas system operates in the urban area of Dublin city centre and surrounding suburbs. Although wind turbine manufacturers such as Enercon [121] and Gamesa [122] have successfully installed wind turbines in urban areas producing renewable energy certain limitations apply. These limitations include planning laws as set out in the Wind Turbine Bill 2012 [123] and wind flow restrictions as a result of surrounding buildings and infrastructure. As a result of the merger between the RPA and the NRA forming TII a significant amount of land and infrastructure is now under the same remit as the Luas network. As a result it may now be more applicable for TII to invest in wind turbines in non-urban areas more suitable from a wind resource point of view. The renewable energy generated from such wind turbines could be supplied to the national grid and the proceeds used to fund the energy consumed by Luas. The energy supplied by any wind farm to the Irish national grid adds to Ireland's renewable energy share and reduces the countries reliance on fossil fuel energy generation. Any increase in renewable energy generation will also help Ireland achieve its binding 2020 renewable energy contribution [24].

Solar energy generation has advanced as a renewable energy source in recent years. There are two forms of solar energy generation. The first is where solar radiation heat is exploited to increase the temperature of water which can then be used in heating systems. The second is where solar radiation is converted to electricity using a Photovoltaic method. Generating electrical energy by converting solar radiation into direct current, by way PV energy generation is another option for the Luas network. Photovoltaic energy generation could be considered for Luas stops or Luas depots. Luas stops energy demand is not excessive and generally follows set trends where there are no daily peaks or surges in consumption [102]. This is ideal for PV, where similar amounts of energy will be generated during winter and summer months. Stand-alone PV systems can be used on localized sites where no grid-connections are required. These systems could be installed on Luas stops shelters to supply supplementary power to Luas stop facilities. A review of Luas stops indicates that 27 of the 32 stops on the Red Line have shelters installed with the surface area facing due south (from south-west through south to south-east). The Luas Green line has 11 of 22 stops with shelters facing due south.

Luas depots have a significant energy demand covering twenty four hours of each day. Although a PV system could not supply the entire energy consumed by Luas depots, the system could provide a supplementary supply which would not require a grid connection. Both Red Cow and Sandyford depots have over 3,000 square metres of available roof space which could cater for a PV installation facing in the due south direction [124]. Such installations like the 50,000 meters squared of solar panels installed on the roof of a high speed rail tunnel on the outskirts of Antwerp have saved significant amounts of energy for its rail operators Infrabel [43]. Considerations as to the type of PV such as those with individual micro inverters on each panel or a central DC to AV inverter for all panels should also be made when planning a PV installation.

5.2.4 Maximum Import Capacity Levels

Each Luas sub-station was designed for a specific capacity rating as previously detailed in Table 12 of Chapter Four. On commissioning of all electrical sub-stations, the maximum import capacity level must be set prior to certification. Maximum import capacity levels are based on the total electrical loading for each sub-station connection and should be set accordingly. Maximum import capacity levels allow the energy providers to determine how much power each connection requires, based on this the electrical grid can be managed to ensure an uninterrupted supply of energy [125]. MIC levels will also have a bearing on the annual connection charge of electricity and the upper limit of the total electrical load each connection has access to. As such MIC levels need be set to the optimal level to ensure an adequate supply of power at the correct connection cost. If the MIC level is set too high the connection charge cost will be considerably higher than required. If the MIC is set too low and the sub-station loading exceeds the MIC, excess capacity charges will apply. The MIC levels of Luas sub-stations have not been analysed for some years, and as a result may be set to high or low incurring additional charges. Analysis of Luas sub-station MIC levels as part of this research required accessing maximum daily consumption values for each sub-station on the Luas system over the winter months. Winter months were considered for analysis as Luas energy consumption increases considerably during these months. The maximum daily loading was extracted using the PS Scada system as detailed previously and was analysed to determine the optimal MIC level for each sub-station. Table 29 details the current MIC levels and their standard connection charges for all Luas sub-stations [126].

Table 29: Current Sub-station MIC Levels

Sub Station	Current MIC Level	Standard Charge
Dundrum	*Out of commission*	
SSG	500	€8,890
Charlemont	500	€8,890
Milltown	500	€8,890
Cherrywood	600	€10,320
Ballyogan	600	€10,320
Glencairn	600	€10,320
Balally	700	€11,910
Carrickmines	800	€13,340
Sandyford	1000	€16,780
Kingswood	500	€8,890
Suir Road	500	€8,890
Kylemore	500	€8,890
O'Connell	500	€8,890
Cookstown	500	€8,890
Heuston	700	€11,910
Saggart	800	€13,340
Cheeverstown	800	€13,340
Spencer Dock	1000	€16,780
Red Cow	1200	€19,790

It should be noted that Dundrum sub-station was out of commission during this analysis and therefore has no set MIC level. Analysis of the maximum daily loads as part of this research for each Luas sub-station for the months of January – March and October – December 2012 indicated nine sub-stations which require MIC adjustment to optimize the levels. In eight locations the MIC needs to be reduced, resulting in a standard charge saving and in one location the MIC needs to be increased, resulting in additional standard charge costs [127].

Figure 81 illustrates the optimal MIC for Spencer Dock sub-station. Spencer Dock sub-station has a rating of 1.6 MW, and has an MIC level of 1000. However as per Figure 81 the maximum daily loading is less than 500 kW. As a result the MIC level is set too high for this sub-station. An MIC of 500 kVA would be the optimal for this sub-station resulting in a significant saving on the annual connection charge.

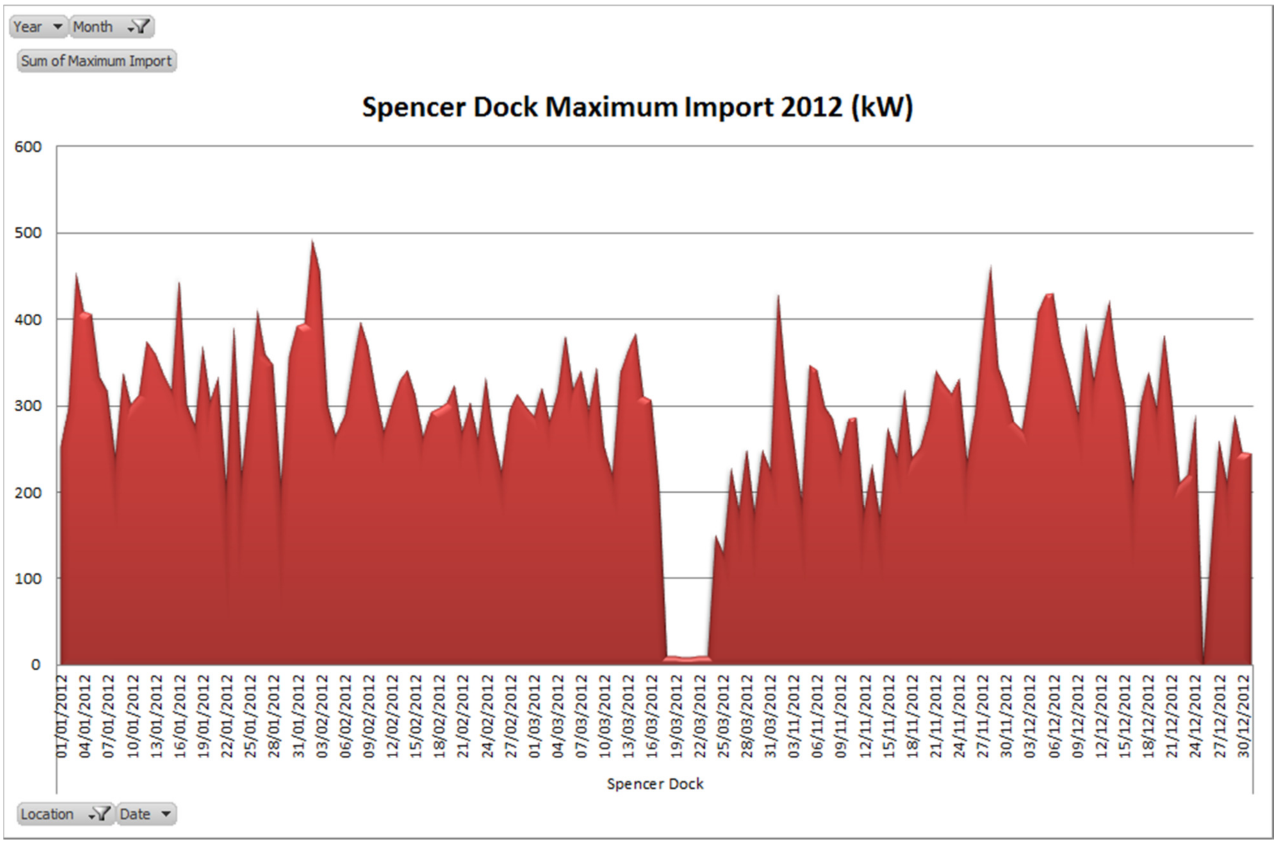


Figure 81: Spencer Dock Maximum Daily Loading 2012

Figure 82 illustrates the optimal MIC for Cheeverstown sub-station. Cheeverstown sub-station is located on the A1 Luas extension. This line has a less than anticipated passenger levels since its opening which has resulted in a reduced Luas service being operated. The current MIC for Cheeverstown is 800 kVA with the maximum daily loading not exceeding 250 kVA normally an optimal MIC for this sub-station would be 500 kVA.

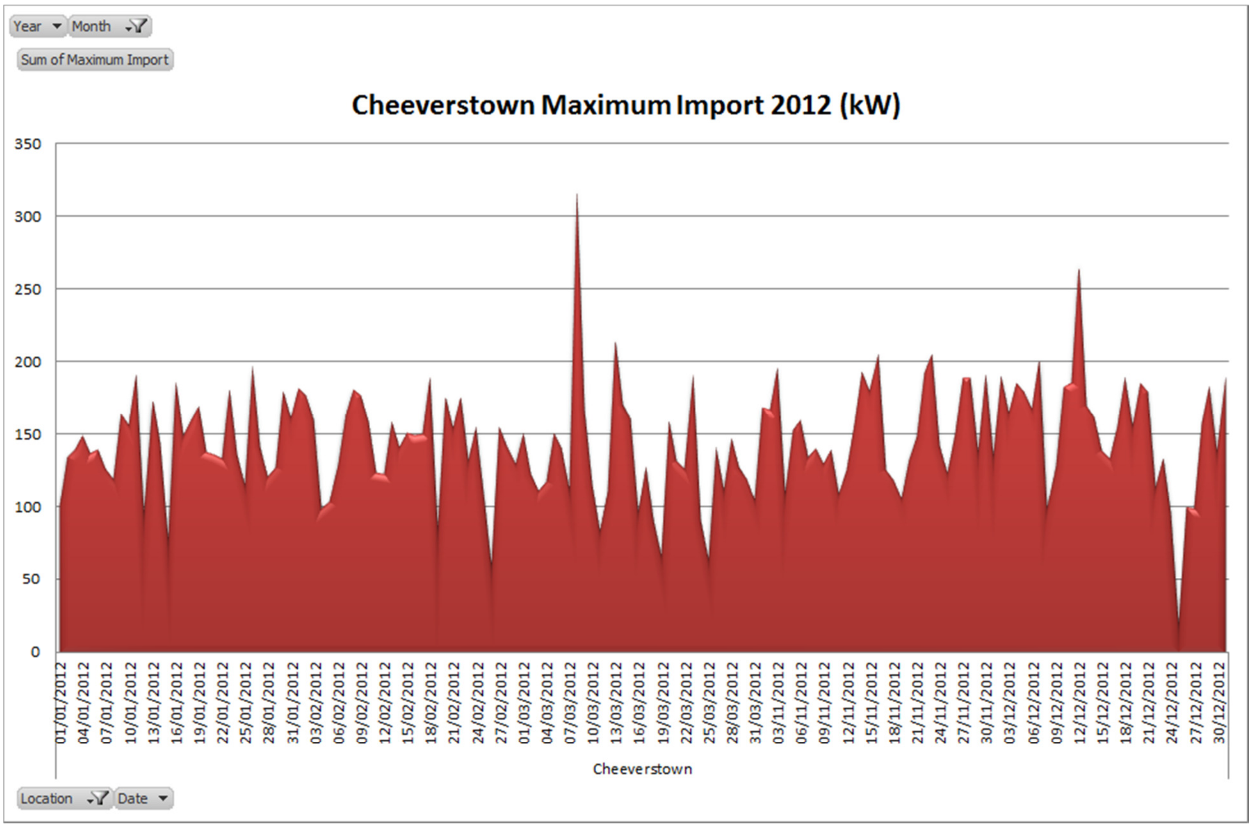


Figure 82: Cheeverstown Maximum Daily Loading 2012

Figure 83 illustrates the MIC adjustment required for Cookstown sub-station. Cookstown was the only sub-station that was found to need an increase in MIC from this analysis. The current MIC for Cookstown is 500 kVA, however this is exceeded on a regular basis and as such should be increased to an MIC of 600 kVA to reduce the amount of excess MIC charges. The saving from excess changes taking into account the additional standard charges equates to €540 per year.

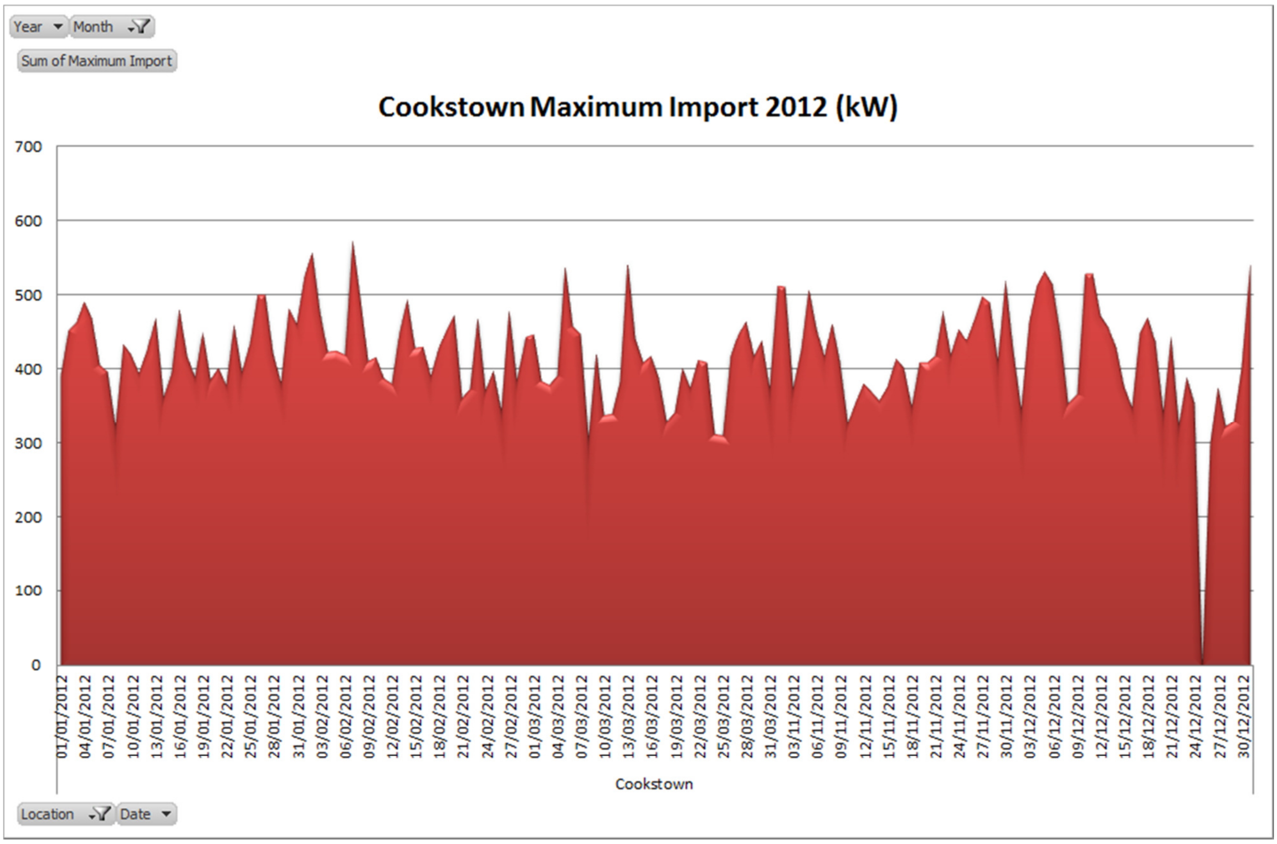


Figure 83: Cookstown Maximum Daily Loading 2012

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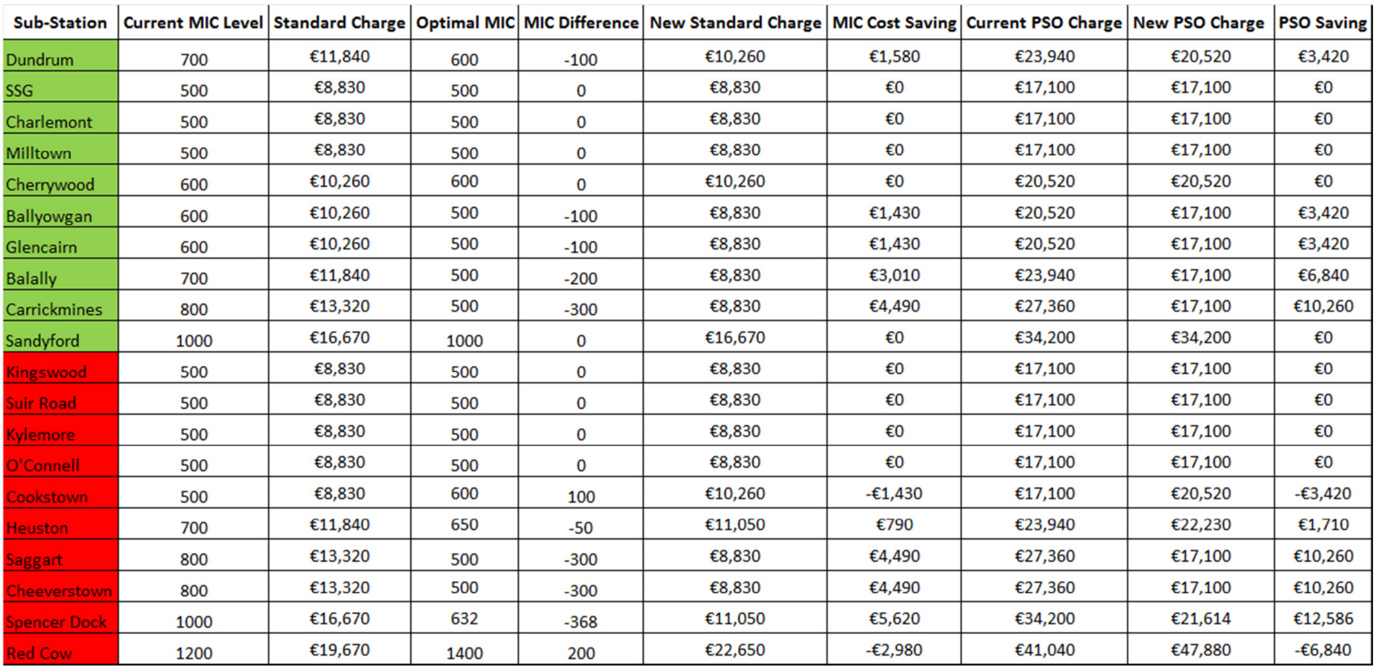
From the analysis of Luas sub-station MIC levels as part of this research it was found that a significant saving in standard connection charges can be achieved by the optimization of these MIC levels. The cost saving breakdown is detailed in Table 30.

Table 30: Optimal MIC levels for Luas Sub-stations



Sub-Station	Current MIC Level	Standard Charge	Optimal MIC	MIC Difference	New Standard Charge	MIC Cost Saving	Current PSO Charge	New PSO Charge	PSO Saving
Dundrum	700	€11,840	600	-100	€10,260	€1,580	€23,940	€20,520	€3,420
SSG	500	€8,830	500	0	€8,830	€0	€17,100	€17,100	€0
Charlemont	500	€8,830	500	0	€8,830	€0	€17,100	€17,100	€0
Milltown	500	€8,830	500	0	€8,830	€0	€17,100	€17,100	€0
Cherrywood	600	€10,260	600	0	€10,260	€0	€20,520	€20,520	€0
Ballyowgan	600	€10,260	500	-100	€8,830	€1,430	€20,520	€17,100	€3,420
Glencairn	600	€10,260	500	-100	€8,830	€1,430	€20,520	€17,100	€3,420
Balally	700	€11,840	500	-200	€8,830	€3,010	€23,940	€17,100	€6,840
Carrickmines	800	€13,320	500	-300	€8,830	€4,490	€27,360	€17,100	€10,260
Sandyford	1000	€16,670	1000	0	€16,670	€0	€34,200	€34,200	€0
Kingswood	500	€8,830	500	0	€8,830	€0	€17,100	€17,100	€0
Suir Road	500	€8,830	500	0	€8,830	€0	€17,100	€17,100	€0
Kylemore	500	€8,830	500	0	€8,830	€0	€17,100	€17,100	€0
O'Connell	500	€8,830	500	0	€8,830	€0	€17,100	€17,100	€0
Cookstown	500	€8,830	600	100	€10,260	-€1,430	€17,100	€20,520	-€3,420
Heuston	700	€11,840	650	-50	€11,050	€790	€23,940	€22,230	€1,710
Saggart	800	€13,320	500	-300	€8,830	€4,490	€27,360	€17,100	€10,260
Cheeverstown	800	€13,320	500	-300	€8,830	€4,490	€27,360	€17,100	€10,260
Spencer Dock	1000	€16,670	632	-368	€11,050	€5,620	€34,200	€21,614	€12,586
Red Cow	1200	€19,670	1400	200	€22,650	-€2,980	€41,040	€47,880	-€6,840

The Public Service Obligation levy for medium voltage energy consumers is also calculated based on the MIC of each site. This Public Service Obligation levy has increased considerable over recent years. The rate applicable to Luas as of January 2015 is €2.85 per month per kVA of MIC. Significant levy savings can also be achieved by optimising sub-station MIC levels. This research recommends optimising the MIC levels for Luas sub-stations to ensure security of supply and also to achieve energy cost savings. To change the MIC level of an electrical sub-station a simple application has to be made to the ESB networks [128].

5.3 Energy Storage Systems

Energy storage systems have the potential to reduce energy consumption by storing the power generated under braking, and supplying this power back to the system when required. Analysis of energy storage system options are detailed in this section of the thesis.

5.3.1 Vehicle Based Super-Capacitors

Energy storage systems (ESS) have developed immensely over the past decade. For light rail systems, ESS can either be vehicle based in the form of super-capacitors or infrastructure based in the form of track side energy storage systems. Vehicle based energy storage systems store the energy generated from braking that would normally be dissipated as heat in the rheostats. Energy storage systems can help increase the realization of regenerative braking systems. Super-capacitor based ESS consist of two solid electrodes in a liquid electrolyte. An iron permeable separator is used to electrically isolate the electrodes, but allowing ions of the electrolyte to pass through. Super-capacitors store charge at the interface of the solid electrodes and the electrolyte, forming a double layer. A capacitance is formed by the two monolayers [47]. The amount of stored energy is a function of the electrode surface area, the size of the ions and the level of electrolyte decomposition voltage. Figure 84 illustrates the configuration of a typical super-capacitor.

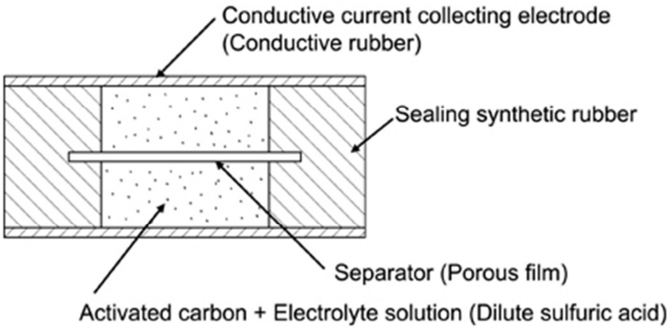


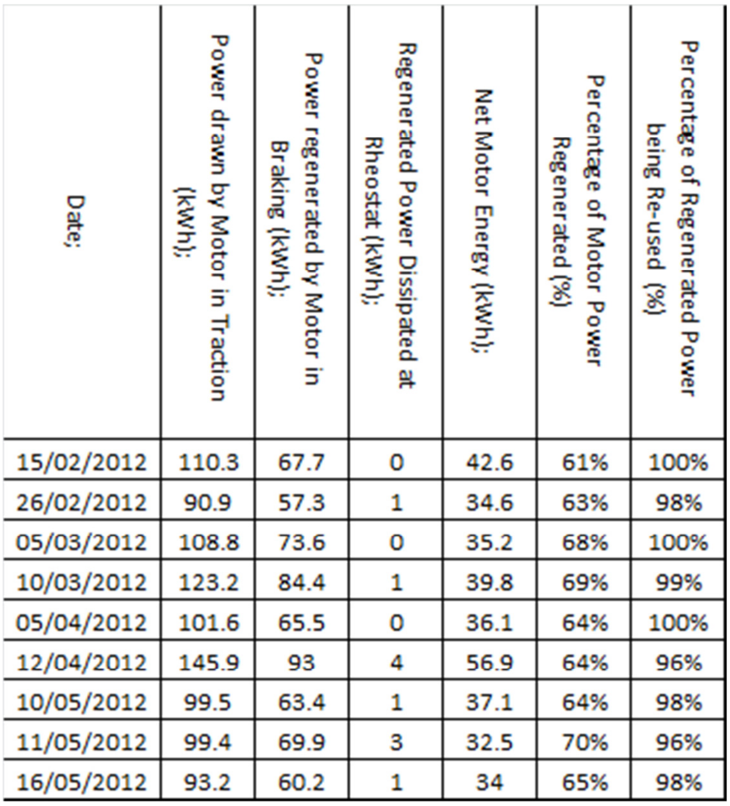
Figure 84: Super-Capacitor Configurations [47]

Super-capacitors have both a high electrical charge and discharge ability, coupled with their longer life cycle and power density and they become an attractive solution for energy storage. Each ESS is made up of a bank of capacitors connected and housed in a single structure [47]. Located on the roof of the vehicle, they generally require no major modifications to be made to the original electrical systems as the super-capacitor unit will be connected in parallel with the regenerative braking system of the vehicle. In braking the energy generated will be distributed between the OCS, tram systems and the ESS, which will charge the capacitors. When the vehicle applies traction, power will initially be supplied by the ESS, once the current requested is too great, power will then be supplied from the OCS. This power flow will be controlled by a new control unit. To determine if the installation of ESS on Luas vehicles would be a feasible project, analysis of vehicle energy consumption and regenerated power on the Red Line took place during this research. Powersoft, a power measurement system was fitted to tram No: 3010 on the Luas Red Line. The system measured power consumed and regenerated by each of the traction motors on the vehicle. Three "EM" 24 Carlo Gavazzi meters were fitted to the 3 phase power cables of the AC traction motors [129]. These meters measured the energy consumed in traction and also the energy generated under braking. A further three meters of similar type were fitted to the rheostat resistors on the roof of the vehicle. These measured the energy being dissipated as heat at 750 V DC. Data measured by each meter was transmitted via a GSM transmitter, with an antenna located on the roof of the vehicle. The data was accessed through the Powersoft desktop software. With this system, energy consumption was accessed by generating historical reports from the system. The percentage error limits of the meters are +1.5% to -1.5%.

Testing took place over a one year period from January to December 2012. These tests were conducted in a range of both operating (peak and off-peak) and weather conditions, Different drivers were used for each test and some of the tests were performed in passenger service and others on trams operating without passengers.

The initial results of the testing concluded that on average 65% of total energy consumed by the traction motors while in traction, was being regenerated in braking. This was over a full loop of the test track (in-bound/out-bound), for trams operating in normal passenger service. Of the 65% of energy being generated in braking, it was found that on average 98% of the energy was being re-used by the system, as shown in Table 31 [130].

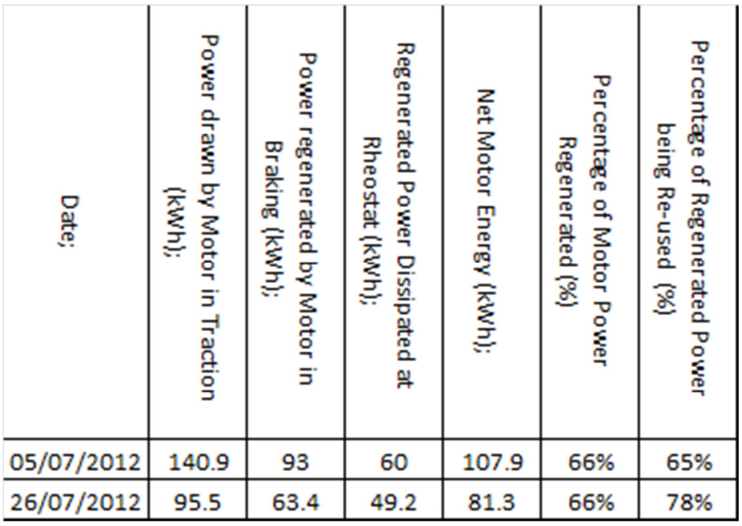
Table 31: Regenerative Braking Test Results



Date;	Power drawn by Motor in Traction (kWh);	Power regenerated by Motor in Braking (kWh);	Regenerated Power Dissipated at Rheostat (kWh);	Net Motor Energy (kWh);	Percentage of Motor Power Regenerated (%)	Percentage of Regenerated Power being Re-used (%)
15/02/2012	110.3	67.7	0	42.6	61%	100%
26/02/2012	90.9	57.3	1	34.6	63%	98%
05/03/2012	108.8	73.6	0	35.2	68%	100%
10/03/2012	123.2	84.4	1	39.8	69%	99%
05/04/2012	101.6	65.5	0	36.1	64%	100%
12/04/2012	145.9	93	4	56.9	64%	96%
10/05/2012	99.5	63.4	1	37.1	64%	98%
11/05/2012	99.4	69.9	3	32.5	70%	96%
16/05/2012	93.2	60.2	1	34	65%	98%

These results were surprising, over the nine test runs in various passenger service conditions, on average only 2% of the regenerated power was being dissipated as heat through the rheostats located on the roof of the vehicle. These results could not justify the investment in ESS, and in fact proved the efficiency of the Luas system. In order to verify the results, a further two tests were performed during engineering hours. Engineering hours are the hours between 02:00 and 05:00, where there are no passenger service trams on the main line. As a result there is no other vehicle on the line which may consume the energy generated during braking from the test tram. From these tests it was observed that the energy generated from braking stayed consistent at 66%. However of this 66%, on average only 28% was being re-used by the system. This resulted in 78% of the energy generated in braking being dissipated as heat through the rheostats as shown in Table 32.

Table 32: Regenerative Braking Test Results



Date;	Power drawn by Motor in Traction (kWh);	Power regenerated by Motor in Braking (kWh);	Regenerated Power Dissipated at Rheostat (kWh);	Net Motor Energy (kWh);	Percentage of Motor Power Regenerated (%)	Percentage of Regenerated Power being Re-used (%)
05/07/2012	140.9	93	60	107.9	66%	65%
26/07/2012	95.5	63.4	49.2	81.3	66%	78%

The reason behind the sudden increase in the percentage of energy being dissipated through the rheostat between in-service and engineering operations was that during engineering operations there are no other vehicles on the line or specifically in the same electrical section, which can harvest the regenerated energy. As a result the OCS reaches its maximum voltage of 900 V and is no longer receptive. The excess energy generated from braking must then be dissipated as heat through the rheostats. These two tests verified the results from the original passenger service testing. When a number of trams are in operation the energy generated in braking can be harvested by the system. As a result of this testing it was determine that Luas system is particularly efficient during peak operations, where 94% of the energy generated in braking is re-used by the system. During off-peak operations the energy being re-used by the system remains upwards of 80% [130].

5.3.2 Track Side Energy Storage Systems

Track side energy storage systems operate on the same basic principles as vehicle based energy storage systems only on a larger scale. Trackside energy storage systems can store the energy that is distributed back to the OCS if no trams are in the electrical section to capitalise on this energy. As a result the OCS will remain receptive for a longer period and can accommodate more energy from braking than normal. Once a tram enters the electrical section where the track side energy storage system is located and draws traction, the initial power will be supplied from the track side energy storage system, rather than the sub-station which is drawing power from the electrical grid. As a result savings can be made in overall energy consumption. In order to justify the installation of track side energy storage systems a comprehensive analysis of power flow through the OCS system and sub-station would first have to take place. Track side energy storage system can only harvest the energy sent back to the OCS in the electrical section where it is installed. Track geometry and line speed will have a major impact on the amount of regenerated energy sent back to the OCS in each electrical section. Testing from the tram based energy meters indicates that on average 65% of total energy is regenerated under braking and of this 98% is reused by the system. These results verify the efficiency of Luas vehicles. Track side energy storage systems may in the future prove to aid in the reduction of energy. This research concludes that track side energy storage systems could not be justified based on the current efficiencies of the Luas system and based on current operating parameters. Should the operation of the Luas system change considerably in the future, track side energy storage systems could be investigated further [131].

5.3.3 Reversible Sub-stations

Reversible sub-stations are another form of technology which could potentially reduce overall energy consumption. Working on the same basic principles of track side energy storage systems, reversible sub-stations harvest the energy generated under braking through the OCS. Where reversible sub-station differs, is that the power is supplied back to the grid instead of being stored in a medium and re-used by the system. This creates a fresh revenue stream for rail operators and can lead to offsetting the cost of energy consumption from each sub-station. Reversible sub-stations require major capital investment and modifications to existing conventional sub-stations. As a result of the efficiencies determined from testing throughout this research it would not be feasible to modify existing Luas sub-stations at present. Reversible sub-stations could be an option in the construction stages of Luas Cross City. The cost of installing a reversible sub-station at the construction stage would be significantly less than modifying and existing sub-station. Alstom have designed and tested a reversible sub-station in France. Known as HESOP, the sub-station supplies excess power generated under braking back to the grid as illustrated in Figure 85 [81].

Figure 85: Alstom Animation of HESOP System [81]

5.3.4 Alstom Energy Mapping Trial

As a result of the testing performed throughout this research, Alstom Ireland chose to select Luas for a test of their super-capacitor system known as "STEEM". Testing which started in 2014 involved the instrumentation of one tram on both the Luas Red and Green Lines. This instrumentation included the installation of meters on the main electrical components of the Luas trams. These meters recorded and transmitted energy data while the trams were operating in passenger service. On review of the data after six months in passenger service it was evident that the Red Line tram was not dissipating sufficient energy through the rheostats to justify the installation of a super-capacitor. These results were similar to the results obtained from testing during this research. The Green line tram however was dissipating some energy through the rheostats during off peak operations, specifically at weekends where a reduced service is operated. As a result Alstom took the decision to install the super-capacitor on tram number 5026 on the Green line. The tram entered passenger service operations is June 2015. The results of the trial, which remains on-going are currently being analysed. This testing is a significant opportunity for Luas to assess the potential for energy storage systems across the system and will complement and allow for validation of the results obtained throughout this research [132]. Figure 86 details the main components metered as part of the E-mapping trial. Future papers will details the results of the Alstom “e-mapping” trial.

Figure Key	
M1	Motor Car 1
MIC	Intermediate Motor Car
SC	Static Converter
IC	Intermediate Car (Non Motor)
M2	Motor Car 2
HVAC	Heating and Ventilation System
Rheo	Brake Rheostat
TBE	Traction Brake Equipment
MC	Measure Capitaliser

Figure 86: Schematic of Alstom E-Mapping Components [132]

5.4 Luas Operations

Energy reduction initiatives attributed to operational procedures and changes are detailed in this section of the thesis.

5.4.1 Optimal Driving Styles

Monitoring and analysing tram energy consumption throughout this research indicated that the differences in energy consumption between drivers for the same journey section can be as high as 60%. Increased tram energy consumption is as a result of aggressive driving styles where maximum traction is used from a stop position, until maximum speed is reached in the shortest time. During initial driver training no major focus is put on efficient driving, mostly due to the fact that the most efficient driving style has not been established for Luas trams. Based on this research the optimal driving style for the Luas Red Line vehicles was established after a significant testing process. In essence the optimal driving style to consume the least amount of energy consumption of Luas vehicles involves using moderate traction and moderate braking techniques. Tram traction and braking is controlled by a master controller unit within the drivers cab as shown in Figure 87.

Figure 87: Luas 401 Master Controller [133]

The master controller has a number of positions including traction, coasting, normal service braking and maximum service brake. Luas vehicles employ a rolling resistance and friction between the wheel and rail. In order to overcome this rolling resistance and friction, the master controller should be put in full traction from a stop position. Once the tram has moved over 5 meters and reached over 5 km/h the rolling resistance is greatly reduced. The master controller should then be reduced to 50% of full traction until line speed is reached. Once line speed is reached the master controller should be positioned in the coast position. The coast position should be maintained for as long as possible. If the speed of the vehicle is reducing on an increased gradient section of track the master controller can again be put to 50% of traction to increase the speed. On approach to a junction or Luas stop, braking should be activated in advance of the stop location. The master controller should be put 50% into the normal service brake position for the entire period until the vehicle has come to a complete stop. Maximum service brake should not be used unless in an emergency situation. Adopting this driving style, the net energy consumption for a tram operating the 32.2 kilometre loop of the Red Line from Tallaght to the Point stop and back to Tallaght is as low as 1.13157 kWh/km. These results omit the power consumed by the heating and ventilation system, as this system cannot be affected by driving styles [134]. During this research it was found that, when compared to the optimal driving style energy consumption of 1.13157 kWh/km, consumption for identical tram trips can vary by up to 60% per driver. As a result there is an ample opportunity to reduce energy consumption considerably by introducing this optimal driving style. To introduce this optimal driving style, significant training would have to take place to enhancing driver's knowledge of the technical aspects of the tram, such as the traction motors and master controller. During the testing for the optimal driving style and eventual final test both the tachometer and front facing CCTV footage were obtained from the tram. The tachometer provides speed and master controller position data relevant to each section of track accurate to one meter. The front facing CCTV provides a video of the entire line. It is proposed to construct a driver training video where the speed, master controller and optimal driving style energy consumption will be displayed on the front facing CCTV footage. This can be used to visually train drivers how to drive Luas trams in an efficient manner. A screen shot of the proposed driver training video is detailed in Figure 88.

Figure 88: Screen Shot of Driver Training Video

A master controller unit could also be used during this training, to simulate the optimal positions. Drivers could practice the moderate traction and braking techniques. After the theoretical training, drivers should be trained on the main line. Using tram number 3010 on the Red Line, the driver's energy consumption can be monitored and assessed. At all times during the efficient driver training, it should be communicated to drivers that safety must take precedence. Other rail operations which have adopted efficient driver training have achieved savings of between 5% and 10% [71]. There is no reason why this cannot be achieved on the Luas Red Line. A 5% reduction in traction energy would equate to 610,000 kWh per year, or 1,220,000 kWh for a 10% saving on the Red Line. Once all drivers have had both theoretical and practical training, an efficient driver competition could potentially be launched. Efficient driving competitions were adopted by DB on their AGV high speed mainline [71]. After training of all their drivers, on-going monitoring and an energy efficiency competition between driver's, savings of total traction power of 5% were achieved. Before such initiatives are implemented safety considerations must be taken into account. At all times safety should be the number one consideration for the operation of a light rail system. However it has been proven that rail systems can be operated in a safe and efficient manner, reducing energy consumption and increasing sustainability. An efficient driving style and related training should also be adopted on the Green Line. Before this can be achieved at least one tram must have energy meters installed similar to that of tram 3010 on the Red Line. If efficient driving training was adopted across both Luas lines, resulting in a 5% saving in traction power, the energy saving to Luas would be in the region of 1,050,000 kWh per year.

5.4.2 Depot Power Management

Luas depot sub-stations consume the highest annual energy consumption across the system. Luas depots located at the Red Cow and Sandyford house the fleet of 66 Luas trams during periods of non-passenger operations. Luas depots also provide maintenance facilities in both depot workshops. Inevitably with the high number of trams stable in both depots each night the energy consumption is significant. Prior to this research no process existed to actively manage Luas depot energy consumption. This results in the potential for tram vehicles to be left in a prepped state for long periods of time. A prepped Luas tram can consume a maximum of 100 kW [104]. Once monitoring of energy consumption was established during this research it was quickly identified that both Luas depots were consuming significant amounts of energy on a daily basis. Based on the analysis of historical data it was identified that after a sustained period of low temperatures during the winter of 2010/2011 the energy consumption of both Luas depot increased to an all-time high. As part of this research new processes were introduced in 2012 to actively manage the energy consumption of each Luas depot. The first process ensured all trams were de-prepping once they had been parked on a storage lane after passenger service or after maintenance. This process was introduced to both Luas drivers and maintenance staff who shunt trams within the depot. The second process which was introduced was for the cleaners of Luas trams to use the access key switch to enter and clean trams. The access switch is located on the exterior of the tram and enables the doors and activates the internal lighting systems which allow cleaners to clean trams. Prior to this, the cleaners were prepping trams which resulted in all the tram systems being activating when they were not required. After cleaning, the access switch is closed and the tram returns to the de-prepped state. Both these processes resulted in no trams being prepped in the depots when they were not required. These new processes required new training for three different companies, including Transdev drivers, Alstom maintainers and Carlyle cleaners. Alongside this new process, new checks were put in place to ensure no vehicles were prepped unnecessarily. Alstom shift production managers checked the depots on two occasions throughout the day. Transdev central control room traffic supervisors also performed a check during the night. To assess the effectiveness of these new processes, the daily energy consumption of Luas depots was monitored. This required the creation of a depot power template within the PS Scada system. Each morning a report was generated from PS Scada for the depot power of both Red Cow and Sandyford depots for the previous day. The data was manipulated in Excel using a macros formula and displayed on a daily depot energy graph. A threshold was established for the daily energy trend for both winter and summer months. The daily depot energy graph was sent to all the relevant parties each day. If the thresholds were breached explanations would be required as to the reasons for this. The weekly depot energy results were also reviewed at the weekly operations meeting attended by senior management of Transdev and Alstom. Figure 101 details the depot energy consumption for the past three years. A significant increase can be noted during December 2012 this was due to sustained period of low temperatures. Once the temperature drops below 0°C, the decision was taken to prepped trams 30 minutes before their departure time. This is to allow the sophisticated computer systems on Luas trams to "warm up" ensuring reliability of the fleet. During the summer months of 2012, 2013 and 2014 both Red Cow and Sandyford depots achieved the minimum base line energy consumption. Due to the activities at each depot it is not possible to reduce the energy consumption further than this level as shown in Figure 89. [135]

Note; There was a fault with the PS Scada system in the Red Cow in June 2013.

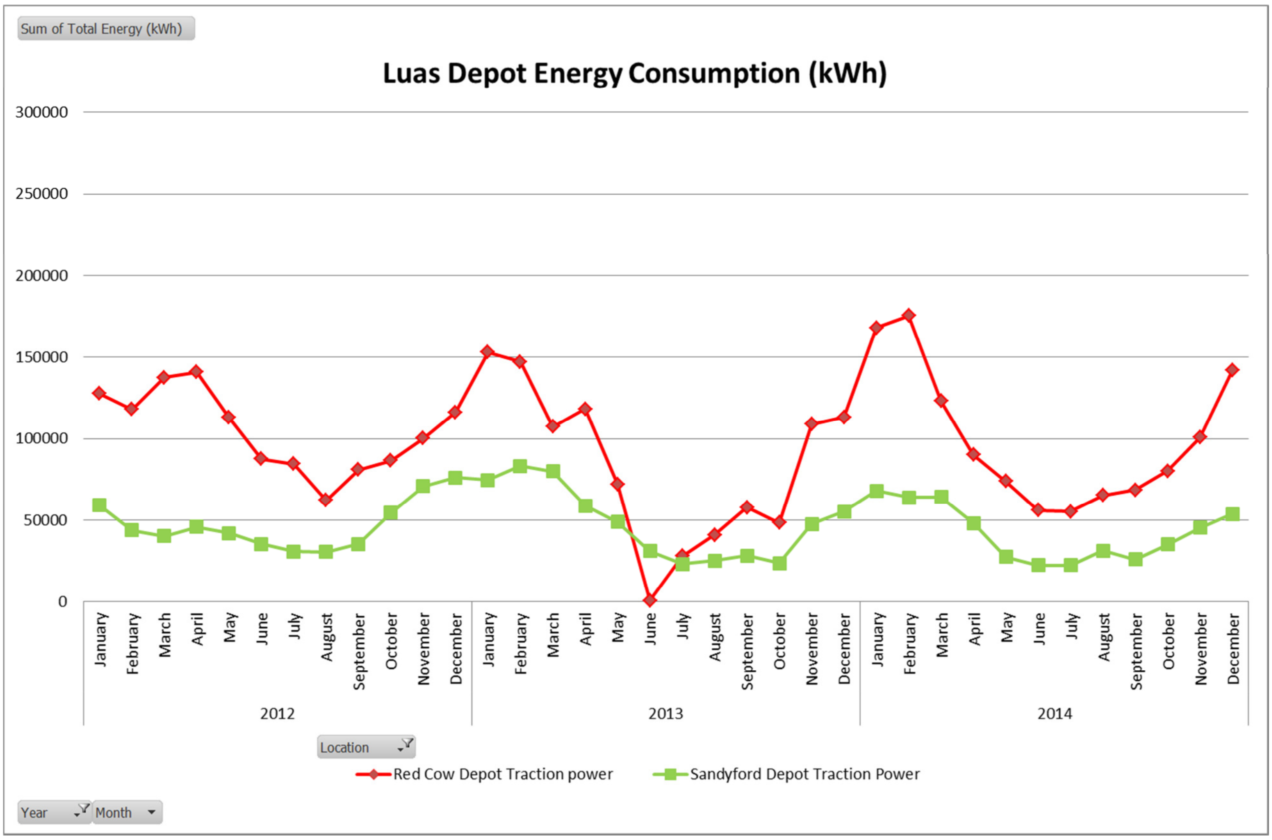


Figure 89: Luas Depot Energy Consumption

Figures 90 and 91 detail the daily depot energy graphs which are distributed and reviewed daily. To benchmark the process, the consumption is based on the previous year's average daily total. Weather conditions are also factored in when reviewing the energy consumption.

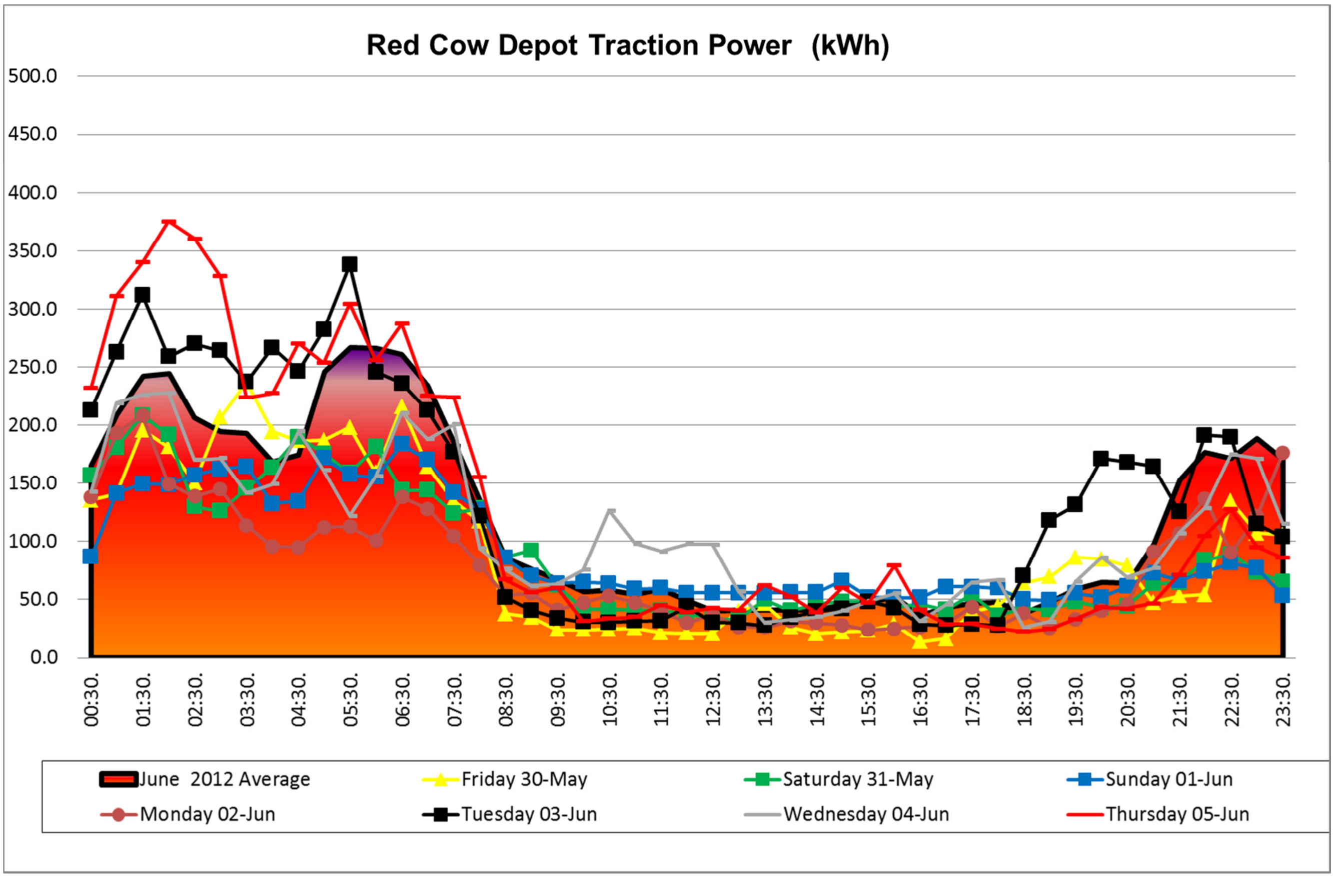


Figure 90: Luas Red Line Daily Depot Power

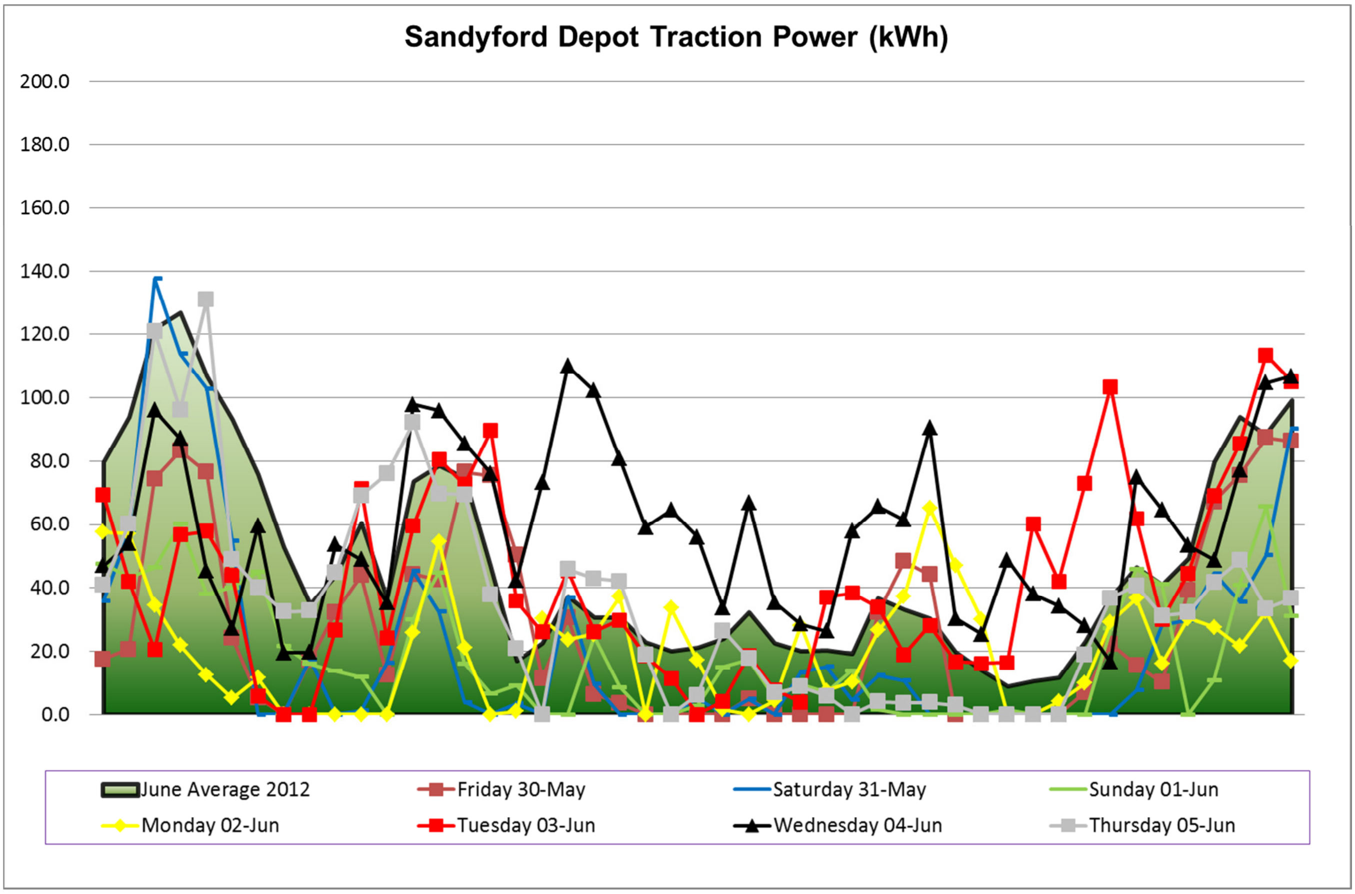


Figure 91: Luas Green Line Daily Depot Power

Since the process to actively manage the energy consumption at both Luas depots was introduced as a result of this research, significant savings have been achieved. The reduction in energy from the winter period of 2012 when compared to 2011 was 20% at the Red Cow depot. During the summer months of 2013 the base line energy load was maintained. The depot energy process and monitoring is an on-going activity which has resulted in the minimum energy consumption being consumed at Luas depots throughout the year [135].

5.4.3 Performance Monitoring

This research has gathered and analysed energy consumption data of the Luas systems from 2011 through to 2014. This was achieved through the manipulation of existing systems including PS Scada, the implementation of new energy monitoring systems including Powersoft, the specific testing of Luas components and the requesting and collecting of data from the Meter Registration System Operator (MRSO) [136]. This research recommends the on-going performance monitoring of Luas energy consumption. Performance monitoring is a key element of energy management. In order to reduce energy consumption, the energy demand must first be established. This research has also identified areas where excessive energy was being consumed and has proposed solutions to reduce this energy. As these energy reduction initiatives are implemented, Luas energy consumption should continue to be monitored to confirm and verify any reductions achieved as a result. Data for Luas medium voltage sites (sub-stations) was obtained from the MRSO on a monthly basis. Once received, this raw data was analysed to determine the energy consumption across the system. The monitoring of medium voltage energy consumption allowed for accurate forecasting of future energy consumption needs. Factors influencing energy consumption including air temperature and operational timetables should be reviewed in conjunction with energy forecasting. For example during winter month’s energy consumption will be significantly higher than that of summer months. Changes to the passenger service operating timetable will also have a direct effect on energy consumption. Figure 92 shows the trending of Luas medium voltage energy consumption throughout this research, the raw data was supplied from the MRSO.

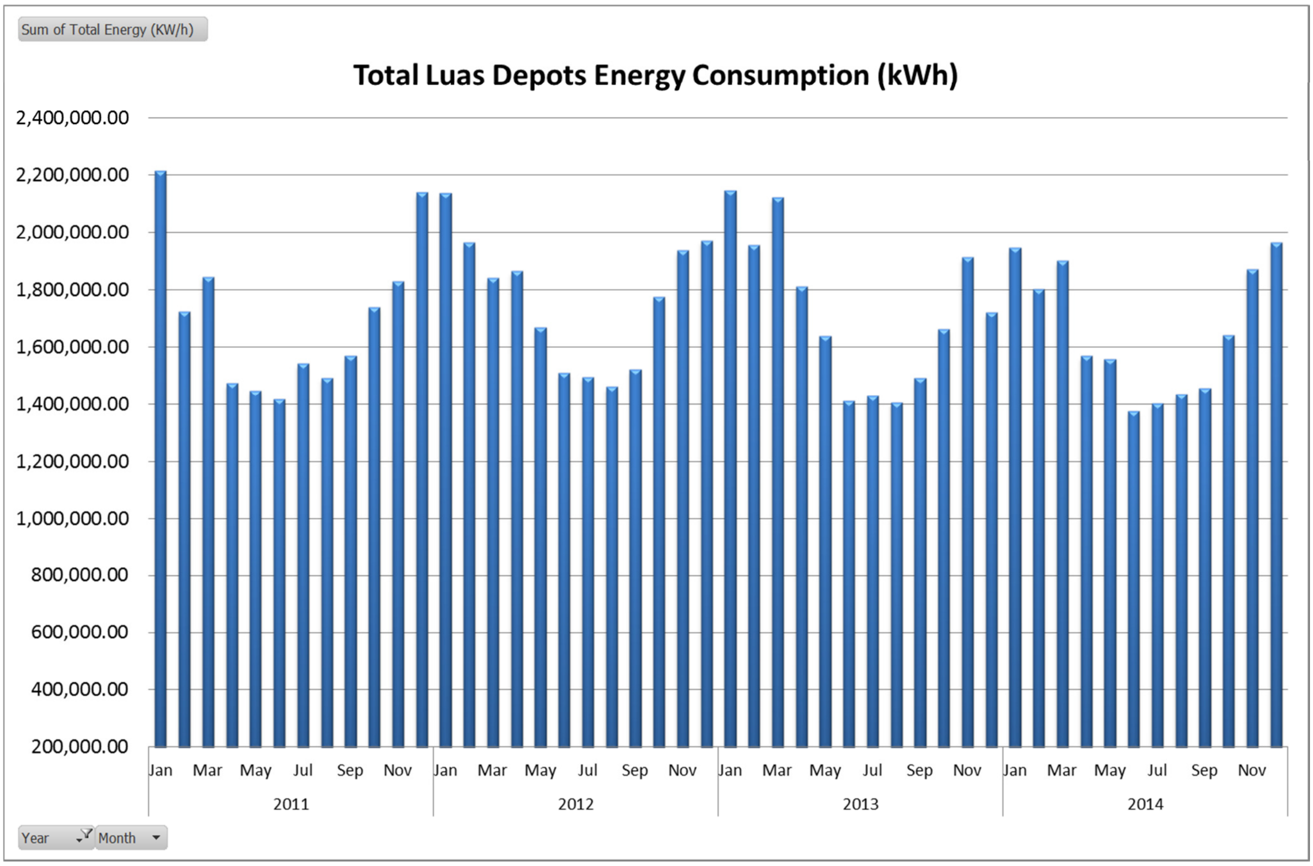


Figure 92: MRSO Energy Consumption Data [102]

As part of this research, PS Scada was manipulated to produce energy consumption reports for all Luas sub-stations and depots. The report application has become a very useful tool in the on-going monitoring of Luas energy consumption. Where the MRSO data was supplied on a monthly basis, Scada was accessed on a daily basis from the Luas depot to assess energy consumption for a specific day or period. Scada was a useful tool, used to determine short periods of energy consumption which are required as a priority. The raw data produced by PS Scada required re-formatting when extracted from the PS Scada reports application. To aid in this, an Excel Marco was created which automatically manipulated the data from the 2 minute intervals to an average 15 minute interval. PS Scada has also been manipulated to produce stray current reports for the Luas system. Negative to earth, and stray current collector cable values were extracted for each Luas sub-station. This research recommends the monitoring of stray current on a regular basis. This will ensure the security of neighbouring infrastructure and also determine the efficiency of the Luas electrical system. Annual, quarterly and monthly performance monitoring and reporting of Luas energy consumption will allow for accurate control over energy consumption. During this research Luas energy consumption was reported to the RPA at the quarterly Environmental Impact Steering Group meetings. Metrics such as kWh per kilometre travelled and kWh per passenger carried were reported and discussed. These metrics can be used to benchmark Luas efficiency against similar light rail operations throughout Europe.

Chapter 6: *Benefits of Change*

6.1 Return on Investment

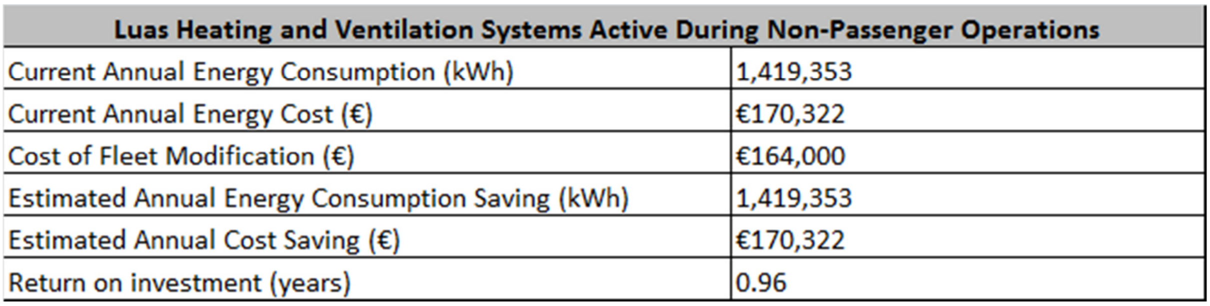
This research has identified a number of energy reduction initiatives, which can be implemented across the Luas system. Where the required resources were available, these initiatives have been implemented throughout the research, and have resulted in energy savings. Projects which require more significant capital investment, such as modifications to Luas rolling stock heating and ventilation systems and the optimal driving techniques have been brought through the design and testing phase and are ready for implementation if capital funding becomes available. To determine the feasibility and merit of the energy reduction initiative identified as a result of this research, a return on investment was calculated for each. Where possible the accurate costs for the implementation of each initiative were established. The estimated savings from each initiative were then used to determine the return on investment period. In calculating the return on investment some assumptions had to be made. Allowances should be factored for minimum order quantities, bulk purchasing and existing Luas contractual arrangements, which may have a positive or negative impact on the final cost of each initiative.

Cost to benefit ratios were also calculated for each energy reduction initiative. Cost to benefit ratios allow for the ranking of a number of projects to determine which should be prioritized based on the current value of the benefits and the current value of costs associated with implementation of the project. The cost to benefit ratio for each of the energy reduction initiative identified throughout this research is based on the estimated economic lifespan of the project.

In order to establish the savings from each project, the cost of energy had to be established. The majority of Luas energy is supplied through the systems sub-stations. The incoming supply to Luas sub-stations from the national electrical grid is at 10.5 kVa medium voltage. This medium voltage supply is known as “Business Demand, Distribution Use Of System (DUoS)” [35]. Medium voltage connections to the national grid attract many fixed charges for security of the supply. Depending on the energy supplier and energy supply contract both the fixed and variable rate charges will vary. A review of the stated charges for medium voltage supplies from the leading Irish energy suppliers indicates that on average 26% of costs are fixed and 74% are variable [137]. The fixed costs are composed of standings charges, capacity charges, and the public service obligation levy. All three of these fixed costs will be affected depending on the maximum import capacity of each medium voltage connection. The variable costs include the unit rates per kWh of energy consumed. These rates vary between suppliers and can include summer and winter tariffs, weekday, weekend day, night and peak. The difference between unit rates per tariff can be as high as 144% with the cheapest tariff generally being the summer night and the most expensive being the winter peak. For the basis of estimating the cost savings as a result of the energy reduction initiates identified throughout this research the following calculation was made to determine the average unit price (AUP) of energy. The average charges including fixed and variable from Airtricity, Electric Ireland and Energia were consulted, these charges were then applied to the average Luas energy consumption for the entire medium voltage supply over the previous five years (2010-2014). The total cost was then divided by the total kWh consumed which resulted in an AUP of €0.121. This average unit price includes both fixed and variable charges and is an average of the present market offers.

The modification of Luas heating and ventilation systems across the fleet of 66 trams has been estimated to cost in the region of €164,000 including materials and labour. This cost has been provided by Alstom, who as the original engineering manufacturers and current maintainers of Luas trams and would be the preferred contractor to carry out this modification. This cost covers both modifications, to automatically disable the systems when in traction and while in the shunt locations as discussed in Chapter five. The return on investment period for this modification has been estimated to be 0.96 years as detailed in Table 33. The annual energy saving is equal to that of the current energy consumption as this modification will disable the system completely when not required.

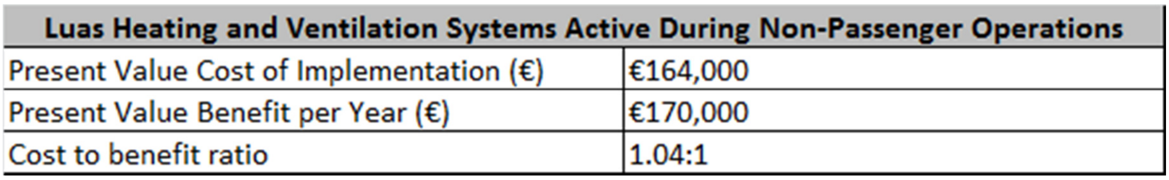
Table 33: Return on Investment for Heating and Ventilation Modification



Luas Heating and Ventilation Systems Active During Non-Passenger Operations	
Current Annual Energy Consumption (kWh)	1,419,353
Current Annual Energy Cost (€)	€170,322
Cost of Fleet Modification (€)	€164,000
Estimated Annual Energy Consumption Saving (kWh)	1,419,353
Estimated Annual Cost Saving (€)	€170,322
Return on investment (years)	0.96

The cost to benefit ratio of this modification is 1.04:1 indicating a return in less than one year as detailed in Table 34. The estimated economic life span of this project is 24 years. This has been estimated based on the asset life of the Luas rolling stock of 35 years minus the 11 years of operation currently conducted. Rolling stock maintenance and overhaul programmes allow for the continued operation of tram systems throughout the asset life. While some sub-components may be required to be replaced during maintenance this will not impact on the modification to disable the heating and ventilation system while operating non-passenger operations.

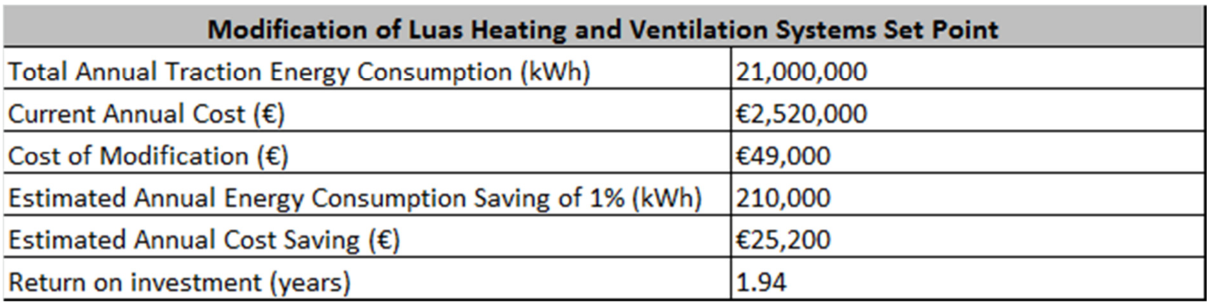
Table 34: Cost to Benefit Ratio for Heating and Ventilation Modification



Luas Heating and Ventilation Systems Active During Non-Passenger Operations	
Present Value Cost of Implementation (€)	€164,000
Present Value Benefit per Year (€)	€170,000
Cost to benefit ratio	1.04:1

The third modification of the heating and ventilation system which concerns adjusting the set point formula has been estimated to cost €49,000 for the fleet of 66 Luas trams. This cost includes the software, hardware and installation on each tram. As tram maintainers Alstom would be the contractor that would carry out this modification. The total energy savings from this modification are difficult to estimate until it has been rolled out across the fleet and the energy consumption monitored and analysed. The heating and ventilation systems of Luas trams can consume up to 60% of total tram power, a conservative estimated saving of 1% of total traction power would result in a saving of 210,000 kWh per year. Based on these estimated savings the return on investment period has been estimated at 1.94 years as detailed in Table 35.

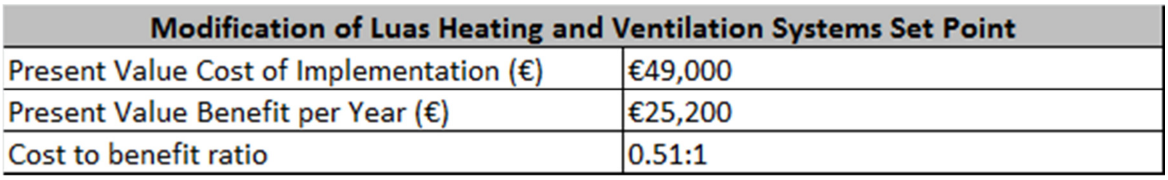
Table 35: Return on Investment for Heating and Ventilation Set Point Modification



Modification of Luas Heating and Ventilation Systems Set Point	
Total Annual Traction Energy Consumption (kWh)	21,000,000
Current Annual Cost (€)	€2,520,000
Cost of Modification (€)	€49,000
Estimated Annual Energy Consumption Saving of 1% (kWh)	210,000
Estimated Annual Cost Saving (€)	€25,200
Return on investment (years)	1.94

The cost to benefit ratio of this modification is 0.51:1 as detailed in Table 36. As with the above modification the estimated economic life span of this project is also 24 years.

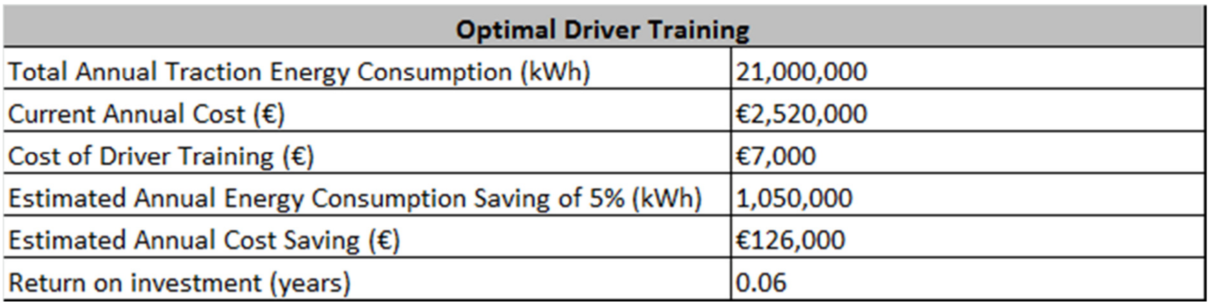
Table 36: Cost to Benefit Ratio for Heating and Ventilation Set Point Modification



Modification of Luas Heating and Ventilation Systems Set Point	
Present Value Cost of Implementation (€)	€49,000
Present Value Benefit per Year (€)	€25,200
Cost to benefit ratio	0.51:1

The implementation of the optimal driving training programme for Luas drivers identified as part of this research will require the installation of a metering system on at least one Green line tram to monitor energy consumption. This metering system will cost in the region of €5,000 and can be linked with the existing Powersoft system. A driver training programme will then have to be developed and rolled out to all Luas drivers. To aid in the driver training programme a demonstration video should be created. The raw data for this video including the tram front facing camera footage, master controller position and energy consumption data has been collected during the research. The creating of the driver training demonstration video has been estimated to cost €2,000 for both Red and Green Lines. The total monetary cost of the optimal driver training programme would be €7,000. It has been estimated that each driver will require at least two full shifts of training for both Luas lines. A driver trainer will also have to be provided for this period. Luas drivers must undergo "driver refresh" training each year, the optimal driver training may potentially be rolled out at this time reducing the amount of hours required per driver. The estimated energy saving of the optimal driving training programme is 5% of total traction power which equates to 1,050,000 kWh or €126,000 per year. Optimal driving styles will not only result in a reduction in energy but will have less negative impact on tram and infrastructure components which may result in reduced maintenance and increased reliability. Optimal driving styles will also be safer and more comfortable for passengers, which may increase overall passenger satisfaction. The monetary return on investment for the optimal driving training programme is 0.06 years as detailed in Table 37.

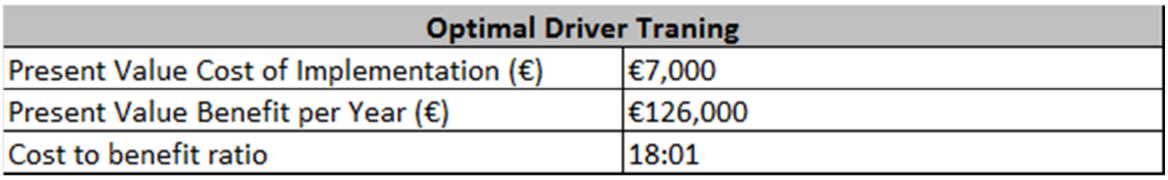
Table 37: Return on Investment for Optimal Driving Training Programme



Optimal Driver Training	
Total Annual Traction Energy Consumption (kWh)	21,000,000
Current Annual Cost (€)	€2,520,000
Cost of Driver Training (€)	€7,000
Estimated Annual Energy Consumption Saving of 5% (kWh)	1,050,000
Estimated Annual Cost Saving (€)	€126,000
Return on investment (years)	0.06

The cost to benefit ratio for the optimal driving training programme is 18:1 as detailed in Table 38. The estimated economic life span of this project is difficult to estimate. As long as the Luas system continues to operate the benefits of this project will be maintained. The asset life of the Luas rolling stock is 35 years, 24 of which are remaining. Should new rolling stock be purchased to replace the existing fleet further driver training would be required at that time to ensure the most efficient operation of said vehicles. The monetary cost of drivers hours required for training has not been included in this cost to benefit ratio, however these cost would be significantly less than the estimated annual savings achieved as a result of implantation of this project.

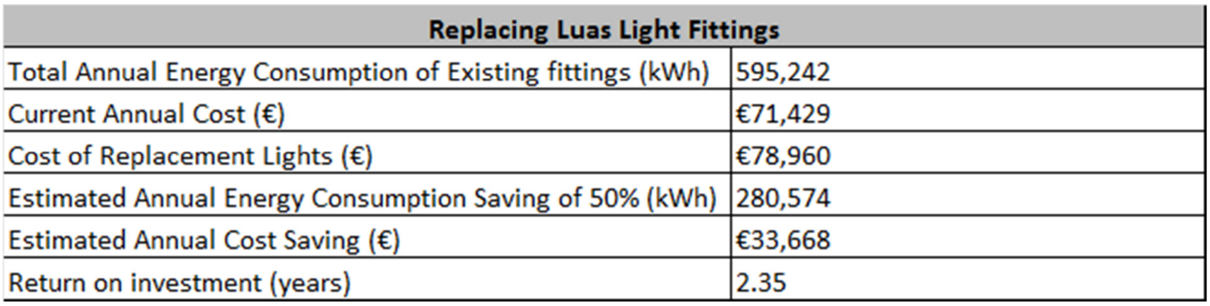
Table 38: Cost to Benefit Ratio for Optimal Driving Training Programme



Optimal Driver Traning	
Present Value Cost of Implementation (€)	€7,000
Present Value Benefit per Year (€)	€126,000
Cost to benefit ratio	18:01

This research has identified significant energy savings through the replacement of light fittings across the Luas infrastructure. The cost to purchase each of the 435 light fittings has been estimated at €78,960. This includes 33 X 200 W fittings at €200 each, 402 X 167 W fittings at €180 each. It is recommended that installation of these fittings would be performed by the facilities maintenance contactors Veolia. The replacement of these light fittings across the Luas system will require significant man hours to install the 430 light fittings. The fittings could be installed all at once or on a fail/replace strategy. Contractual agreements may be made with the infrastructure maintainers regarding the replacement of fittings. As per the 10 year infrastructure annual maintenance plan, the existing light fittings must be replaced every three years. Based only on the cost of the new light fittings the return on investment for this initiative would be 2.35 years as detailed in Table 39.

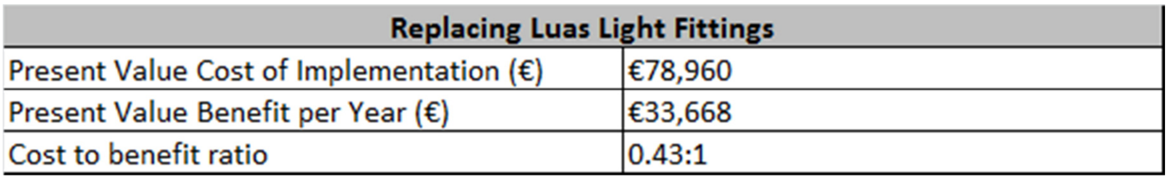
Table 39: Return on Investment for Replacing Luas Infrastructure Light Fittings



Replacing Luas Light Fittings	
Total Annual Energy Consumption of Existing fittings (kWh)	595,242
Current Annual Cost (€)	€71,429
Cost of Replacement Lights (€)	€78,960
Estimated Annual Energy Consumption Saving of 50% (kWh)	280,574
Estimated Annual Cost Saving (€)	€33,668
Return on investment (years)	2.35

The cost to benefit ratio for replacing Luas infrastructure lighting is 0.43:1 as detailed in Table 40. The estimated economic life span of this project is 22 years based on the lifespan of the Induction light fittings and the average activation time per day across Luas infrastructure. Existing contractual arrangements with the current infrastructure maintenance contractors must also be factored when considering this proposal. A replace on fail strategy would serve as the best policy for implementation of this proposal.

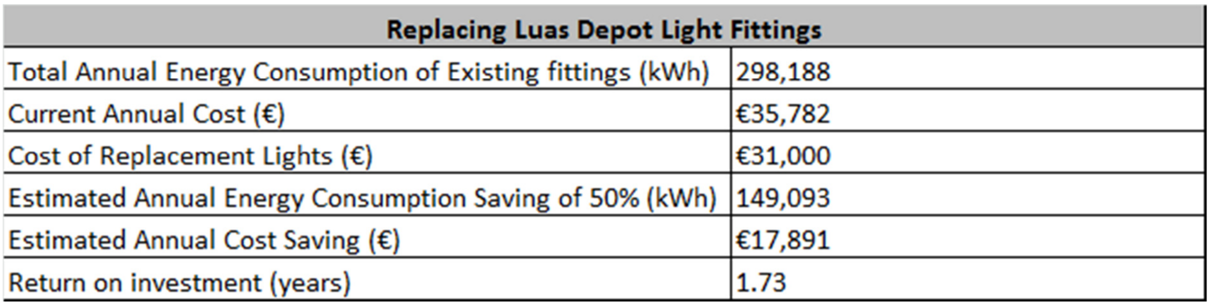
Table 40: Cost to Benefit Ratio for Replacing Luas Infrastructure Light Fittings



Replacing Luas Light Fittings	
Present Value Cost of Implementation (€)	€78,960
Present Value Benefit per Year (€)	€33,668
Cost to benefit ratio	0.43:1

Opportunities also exist to replace the light fittings within Luas depots. As a result of this research it has been identified that the installation of Induction lighting in each Luas depot will cost €31,000. This cost includes the purchase of new lights 130 X 200 W at €200 per fittings and the installation cost of €5,000. The replacement of these fittings for efficient Induction light fittings would result in an energy saving of 149,093 kWh per year. This represents a 50% energy reduction. A test of 16 induction light fittings at the Red Cow depot during this research has confirmed the energy reduction of the fittings. The LUX levels have also been increased with the installation of these new fittings. Maintenance technicians have expressed their satisfaction with the new lighting which has helped to increase overall productivity. Reduced maintenance costs will also be achieved due to the 100,000 hour life of the new Induction lights. Table 41 details the return on investment period for this initiative.

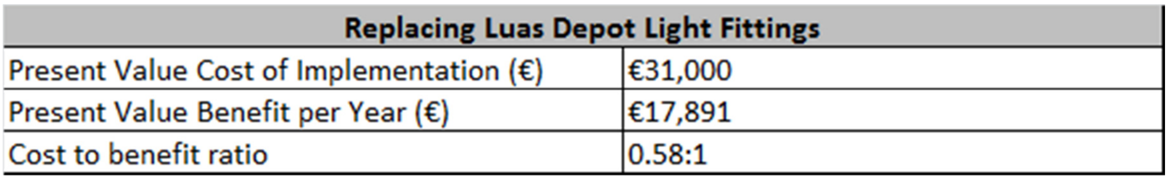
Table 41: Return on Investment for Replacing Luas Depot Lighting



Replacing Luas Depot Light Fittings	
Total Annual Energy Consumption of Existing fittings (kWh)	298,188
Current Annual Cost (€)	€35,782
Cost of Replacement Lights (€)	€31,000
Estimated Annual Energy Consumption Saving of 50% (kWh)	149,093
Estimated Annual Cost Saving (€)	€17,891
Return on investment (years)	1.73

The cost to benefit ratio for replacing Luas depot lighting is 0.58:1 as detailed in Table 42. The estimated economic life span of this project is 11 years based on the lifespan of the Induction light fittings and the average activation time per day across both Luas depots. Existing contractual arrangements with the current infrastructure maintenance contractors must also be factored when considering this proposal. A replace on fail strategy would serve as the best policy for implementation of this proposal.

Table 42: Cost to Benefit Ratio for Replacing Luas Depot Lighting



Replacing Luas Depot Light Fittings	
Present Value Cost of Implementation (€)	€31,000
Present Value Benefit per Year (€)	€17,891
Cost to benefit ratio	0.58:1

As part of this research it was identified that the internal passenger saloon lights could be replaced with LED tubes to reduce energy consumption. The costs for purchasing replacement LED lights for the Luas fleet is €146,718. Each LED tube costs €45 with a 5% discount available for bulk purchasing. The labour cost to replace the interior light fittings on Luas vehicles has been estimated to be in the region of €20,000 for the fleet of 66 trams. As the current maintenance contractors, Alstom would be the preferred contractor to complete this task. The return on investment for this project equates to 7.33 years. This return on investment period is extensive however the increased lifetime of these fittings will ultimately reduce maintenance costs. This should be taken into account when considering this initiative. The LED light fittings will also increase the LUX levels within the passenger saloon of Luas vehicles which may increase safety and customer satisfaction. Table 43 details the return on investment calculation for the replacement of passenger saloon lighting.

Table 43: Return on Investment for Replacing Tram Passenger Saloon Lighting

Replacing Passenger Saloon Lighting	
Total Annual Energy Consumption of Existing fittings (kWh)	394,680
Current Annual Cost (€)	€47,361
Cost of Replacement Lights (€)	€166,718
Estimated Annual Energy Consumption Saving of 48% (kWh)	189,446
Estimated Annual Cost Saving (€)	€22,733
Return on investment (years)	7.33

The cost to benefit ratio for replacing Luas depot lighting is 0.1:1 as detailed in Table 44. Given the low coat to benefit ratio a replace on fail strategy would serve as the best policy for implementation of this proposal over the remaining life of the trams.

Table 44: Cost to Benefit Ratio for Replacing Tram Passenger Saloon Lighting

Replacing Luas Light Fittings	
Present Value Cost of Implementation (€)	€166,718
Present Value Benefit per Year (€)	€22,733
Cost to benefit ratio	0.1:1

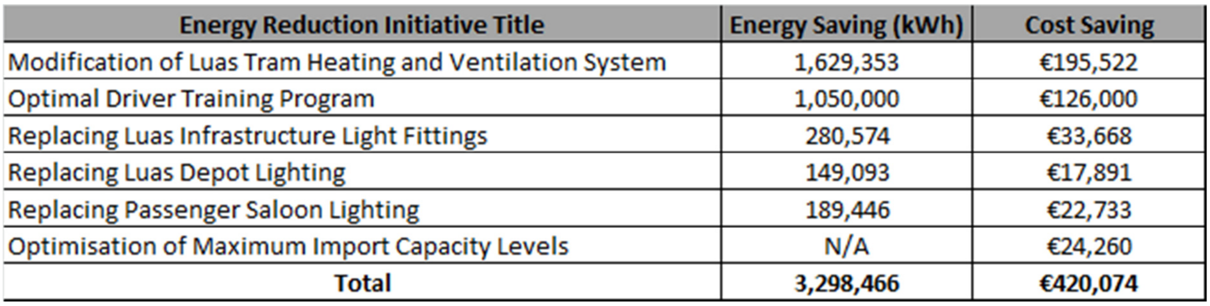
From a review of maintenance records the current florescent tubes fitted to the passenger saloon of Luas rolling stock are replaced on average every five years. Replacing the florescent fittings with LED fittings will increase the lifetime of the lights by 50%. The estimated economic life span of this project is therefore 7.5 years. Having a cost to benefit ratio of 7.3:1 this project, on a purely energy saving basis has an extensive return on investment period. Considerations for a replace on fail approach as well as increased passenger satisfaction and safety as a result of increased LUX levels within the passenger saloon should be taken when decision to proceed with this project.

Analysis of the current maximum import capacity levels of Luas sub-stations as part of this research identified the incorrect setting for a number of sub-stations. Due to the economic downturn and lack of property construction on the Luas line extensions, a reduced service operates in these areas. As a result sub-station MIC levels had been incorrectly set from the day of commissioning. In the initial design stage this lack of development on the Luas extensions was not foreseen and the MIC levels were set based on a projected increased service. Optimisation of MIC levels will result in a significant cost saving, and will also benefit the national grid ensuring a continuous uninterrupted supply. This process will result in an annual cost saving to Luas of €24,260. Sub-station MIC levels should be reviewed on an annual basis, or where changes have been made to the operational timetable to ensure the optimal MIC is set for each sub-station.

As a result of this research new procedures were implemented in both Luas depots to manage energy consumption. Luas depot energy was actively monitored resulting in the identification of trends and thresholds for daily energy consumption. New processes were then implemented to manage depot energy consumption for Luas drivers and Alstom maintenance staff. The result was an initial reduction of up to 60,000 kWh per month based on the previous year's consumption where no depot power management processes existed. The on-going monitoring of energy and the new processes in place, have resulted in the minimum base line energy consumption being established and maintained month on month. In 2013 the lowest monthly energy consumption across both Luas depots was achieved since the start of operation in 2004. No direct costs were incurred as a result of this new process and as a result all energy savings are a net gain to Luas. The depot energy management process has continued beyond this research. Daily energy graphs are distributed and reviewed at the weekly operations meeting. Quarterly depot energy meetings also take place to discuss actions which may help reduce further the depot energy. All Luas stake holders attend these meeting and have an opportunity to bring new ideas to the table.

Table 45 details the potential annual energy and cost savings as a result of the energy reduction initiatives identified during this research.

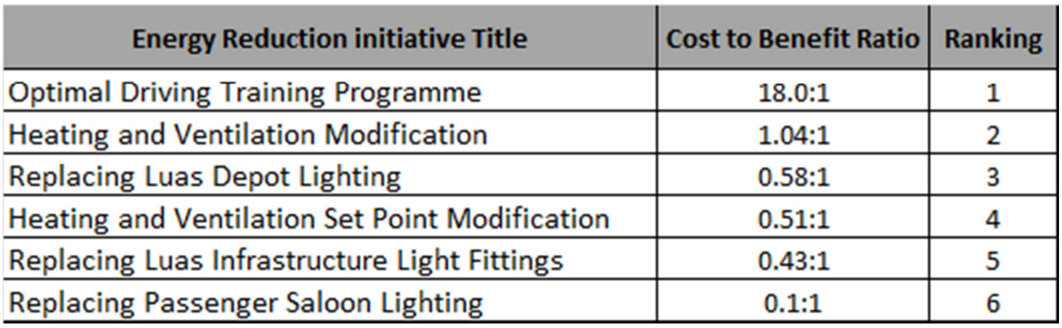
Table 45: Potential Total Energy and Cost Savings



Energy Reduction Initiative Title	Energy Saving (kWh)	Cost Saving
Modification of Luas Tram Heating and Ventilation System	1,629,353	€195,522
Optimal Driver Training Program	1,050,000	€126,000
Replacing Luas Infrastructure Light Fittings	280,574	€33,668
Replacing Luas Depot Lighting	149,093	€17,891
Replacing Passenger Saloon Lighting	189,446	€22,733
Optimisation of Maximum Import Capacity Levels	N/A	€24,260
Total	**3,298,466**	**€420,074**

Table 46 details the ranking of the energy reduction initiatives based on the cost to benefit ratio calculation.

Table 46: Summary of Cost to Benefit Ratio Rankings



Energy Reduction initiative Title	Cost to Benefit Ratio	Ranking
Optimal Driving Training Programme	18.0:1	1
Heating and Ventilation Modification	1.04:1	2
Replacing Luas Depot Lighting	0.58:1	3
Heating and Ventilation Set Point Modification	0.51:1	4
Replacing Luas Infrastructure Light Fittings	0.43:1	5
Replacing Passenger Saloon Lighting	0.1:1	6

This research has achieved the aims and objectives set out, to identify options for reducing energy consumption across the Luas network.

6.2 Sustainability

Luas is committed to offering the public a sustainable alternative to travel by private car in the areas of Dublin to which it serves. To help achieve this RPA and Transdev published the Luas Sustainability Plan in 2011. The Luas sustainability plan set a 15% energy reduction target to be achieved by the end of 2015. The Luas emissions factor of 80 CO_2 g/passenger/km is one of the lowest transport options in Dublin. The ultimate goal is to make Luas the most sustainable travel mode in Dublin. The initiatives identified throughout this research have the capacity to aid Luas to achieve its targets set out in the Luas Sustainability Plan, delivering a national benefit. The expansion of the Luas network continues with the construction of Luas Cross City currently under construction. During 2013 an independent energy efficiency review of the Luas Cross City design took place. The review was independently conducted by the Sustainable Energy Authority of Ireland. As part of the review, the initiatives identified during this research were consulted. Where possible in both the construction and operational stages of Luas Cross city these initiatives will be implemented. This research and its findings have the potential to notably impact the public transport market in Ireland through a reduction in overall energy consumption, the reinvestment of savings achieved and the increased sustainability of Luas. The energy reduction initiatives if implemented have the potential to reduce Luas CO_2 emissions by 2000 metric tonnes.

Chapter 7: *Conclusions and Recommendations*

7.1 Conclusions

The aim of this research was to identify options for reducing energy consumption across the Luas network. In order to achieve this aim the energy demand first had to be established. Significant testing took place throughout the research tenure, and not only was the energy demand of Luas operations obtained it was thoroughly analysed and monitored, this monitoring has also been continued by Transdev. Establishing the energy demand allowed for proposals to reduce energy to be identified, where it was determined that excess energy usage was prevalent. Not only were sophisticated technologies consulted as part of possible energy saving initiatives but simple operational changes and practices were also analysed, some of which, can and have resulted in significant energy savings. While it was not possible to research all energy reduction initiatives those that were consulted and analysed have the potential to substantially reduce Luas energy demand. Some of the energy reduction initiatives recommended as a result of this research will require significant capital investment, others require minor operational and cultural changes. The goal of Luas is to excel in sustainability and achieve even further energy reductions. As a direct result of the research, Transdev and the TII have a greater awareness and a better understanding of Luas energy consumption. This understanding is crucial in saving energy, especially since the scale of the Luas network consumes a significant amount of electricity. On completion of the research, the energy reduction initiatives identified have the potential to reduce energy consumption by over 15% or 3,200,000 kWh. For each initiative, significant on site testing took place to verify the potential energy reductions. Each project was both technically and operationally reviewed by Transdev, TII and DIT to ensure integrity. Further investment is required for the large scale projects such as wind turbine and PV energy generation.

As a result of the research, it is anticipated that Luas will increase its sustainability, which is key in the current economic climate. The energy savings achieved will also allow a potential for further re-investment in rolling stock and infrastructure to improve the Luas system as a whole. The projects identified and implemented throughout the research will provide direct employment for numerous companies during the testing and implementation stages. In addition the DIT researcher and author is now a full time employee within Transdev Dublin, tasked with the implementation of these energy reduction initiatives. The research has brought together a number of companies and resulted in behavioural changes across all Luas staff. Specifically all staff were informed of the high energy consumption being consumed in both Luas depots. Transdev drivers were instructed to “de-prep” (switch off) vehicles once they returned to the depot through a driver’s general notice. Alstom technicians were instructed to de-prep vehicles once maintenance was complete, and Carlyle cleaning staff have been trained to use the access key device to access trams for cleaning. Further awareness of the energy consumption was communicated to management through weekly updates at the operations meeting, and daily energy consumption graphs were emailed to operational members.

The research results have also been considered in the design and future operational stages of Luas Cross City (LCC). The significance of the research has been recognised by light rail operators in Barcelona, Lyon and Paris who are now examining the results and knowledge gained through the research. Through Transdev’s worldwide exposure as a group and TII’s consultancy services outside of Ireland, these projects have been showcased at an international level for other light rail and metro networks. An academic research paper as part of this research has been published. The results and initiatives of the research have also been presented to EU research programmes such as “OSIRIS” energy reduction strategies for transport, and the International Association of Public Transport, (UITP) energy workshops.

7.2 Recommendations and Further Research

The construction of LCC is currently underway, this extension includes the construction of a new maintenance depot at Broombridge. It is recommended that increased energy meters are installed on the Broombridge depot circuits such as the sand and wash plan as well as the depot workshop lighting. These meters can be installed as an extension of the current Powersoft system or as part of a new energy metering system. The LCC project will also include the purchase of seven new tram vehicles which will operate on the Green Line and LCC. It is recommended that at least one of these new trams is fitted with a metering system similar to that of the current system fitted to tram 3010 operating on the Red Line. The installation of such metering devices during the construction period will result in reduced costs when compared to retrofitting once construction has been completed. Additional metering of the new depot and trams will allow for identification of the energy requirements of these new aspects of the Luas network in the future.

An opportunity now exists, following the merger of RPA and NTA forming TII for an investment in wind turbines or a wind farm which would be under the remit of TII. An investment in such a project would increase Ireland’s renewable energy share while also generating revenue for TII to offset the cost of Luas energy consumption. Similar projects have been successfully implemented in countries such as Belgium, while in Tenerife the LRT authority plan to build and maintain a wind farm which will have the capacity to supply the entire light rail network. Further research is required to determine what land is now under the remit of TII which may be suitable for wind turbine installation. Upon identification of suitable land considerations would be required to be made in respect of planning laws and also a wind resource assessment at the proposed location.

Generating electrical energy by converting solar radiation into direct current, by way of Photovoltaic energy generation was also consulted during the research tenure. The ideal application for PV energy generation is at Luas stops or Luas depots. Luas stops energy demand is not excessive and generally follows set trends where there are no daily peaks or surges in consumption. This is ideal for PV, where similar amounts of energy will be generated during winter and summer months. From this research it has been determined that Luas stop shelters or the roof of Luas depot workshops would be the ideal locations for PV panels. It is recommended that further research and analysis of the sun light resource at appropriate Luas stops and also Luas depots is conducted.

7.3 Critical Appraisal

This research has utilised all available data sources in order to establish Luas energy consumption and determine solutions for reducing areas of excess energy. The methodology included the gathering and analysis of a large database of Luas energy consumption. This thesis may be considered to be quite broad however as a result of covering the entire Luas network as opposed to specific components, a number of solutions including technical modifications and operational procedures to reduce Luas energy consumption have been identified.

The research results have contributed to Luas in a number of ways. Luas stakeholders including TII, Transdev and Alstom now have increased knowledge of Luas energy consumption. The research has led to a considerable data base of Luas energy being compiled and processes being put in place for on-going energy monitoring.

The results of this research are being utilised on a daily basis to aid in the on-going strategy for reduced energy consumption across the Luas network. Where technical solutions have been identified and discussed, not all have been brought through to the final solution. In these cases further work will be required before implementation including trailing of specific solutions.

The methodology to gather and analyse Luas energy consumption from all available sources proved invaluable to this research. A large database of Luas energy now exists. One limitation to this methodology was the specific testing of the energy consumption of the 402 style trams operating on the Green Line. No metering system was fitted to a tram operating on the Green Line during the research period. As a result some assumptions had to be made best on the results of testing on the Red Line in conjunction with a technical review of components on the 402 style trams.

The author has recognised that it was not possible to research and present final technical solutions for each energy reduction initiate identified. Where topics such as renewable energy generation are discussed these will require further research in order to establish a final conclusion to their suitability for Luas energy reduction.

This research has not factored the passengers carried by Luas or the commercial aspects of the system. The overall sustainability of Luas will be determined on its ability to transport passengers. When LCC begins passenger service operations in 2017 a review of Luas overall sustainability should be conducted analysing passenger numbers, capital costs and operational costs. Such a review would allow for the benchmarking of the Luas operation from a sustainability point of view with other similar operations through the EU.

List of References

[1] Transdev, “*Luas period report”*, Dublin, Period 12, 2014.

[2] Australian Tourism and Transport Forum, “*The Benefits of Light Rail”* March 2010.

[3] Society of Chartered Surveyors Ireland, *“The Irish Construction Industry in 2012”,* 2012.

[4] Policy Analysis, *Does Rail Transit Save Energy or Reduce Greenhouse Emissions?,* Issue No. 615, April 14, 2008.

[5] Carlos Felipe Pardo, et al, *“Chapter 4 – Sustainable Urban Transport”,* Shanghai Manual – A Guide for Sustainable Urban Development in the 21st Century, United Nations World Expo, 2010.

[6] Jonas Lohmann, Eiljaer Andersen, *“Advantages of Light Rail Transit”,* Technical University of Denmark, May 2012.

[7] Railway Procurement Agency, *“Luas to date”,* Available at, www.rpa.ie/en/luas_lines/Pages/default.aspx, Accessed December 2011.

[8] Alstom Transport, “*Manufacturer’s General Functional Specification”*, courtesy of Alstom, October 2008.

[9] Dublin Transport Initiative, *“final report”*, 1995.

[10] Department of Transport*, “Transport railway infrastructure act”* , 2001.

[11] Railway Procurement Agency*, “Luas Operating Contract”*, 2003.

[12] Department of Transport, “*Luas press release*”, Available at, www.nta.gov.ie/pressReleasesList.aspx, Accessed January 2012.

[13] European Union, “*A Major Economic Player on the World Stage”* European Publications Office, 2006.

[14] European Union, *“Energy Roadmap 2050”,* Final, 2011.

[15] National Academies of Science, “*What You Need to Know About Energy – Supply and Demand*” 2008.

[16] European Union, *“Roadmap to a Single European Transport 2011”,* 2011.

[17] Shift2Rail, “*Overview of Shift to Rail and its preparatory phase”*, Available at, www.shift2rail.org/overview, Accessed June 2014.

[18] Global Mass Transit, *“Global Light Rail Projects Report”,* New Delhi, 2012.

[19] Oman plans public transport systems, Available at, http://www.thenational.ae/world/middle-east/oman-plans-public-transport-system-to-ease-traffic-woes, Accessed November 2014.

[20] The Economist Intelligence Unit, *“Liveability survey”,* August 2014.

[21] Yarra Trams, about us, Available at, http://www.yarratrams.com.au/about-us/who-we-are/facts-figures/, Accessed July 2014.

[22] Babalik, *“Urban Rail Systems: A Planning Framework To Increase Their Success”,* University College London, August 2000.

[23] Kim, et al, *“Analysis of Light Rail Rider Behavior: Impacts of Individual, Built Environment, and Crime Characteristics on Transit Access”,* University of Missouri, November 2006.

[24] The Sustainable Energy Authority of Ireland, *“Energy in Transport Report”,* October 2014.

[25] International Energy Agency, International Union of Railways, *Railway Handbook 2014”*, Paris 2014.

[26] González Gil, et al, “A systems approach to reduce urban rail energy consumption” Newcastle University, January 2014.

[27] Richardson, *“Sustainable Transport; Analysis Frameworks”*, University of Michigan, 2005.

[28] Powell, et al, *"Experimental Assessment of the Energy Consumption of Urban Rail Vehicles during Stabling Hours: Influence of Ambient Temperature",* Newcastle University, February 2014.

[29] Lund, "*Renewable Energy Strategies for Sustainable Development",* Aalborg University, Denmark, 2006.

[30] Kiesseling, et al, *"Schneider Contact lines for electric railways",* Schneider, Siemens, 2nd edition, 2009.

[31] Luas Electrical Infrastructure Specifications, courtesy of RPA, 2011

[32] European Standard, "*Railway applications. Fixed installations. Electric traction overhead contact lines (EN 50119)",* January 2010.

[33] European Standard, *"Railway applications - Fixed installations - Electrical safety, earthing and the return circuit* (EN 50122)*",* January 2011.

[34] Cotton, *"Stray Current Control in DC Mass Transit Systems",* IEEE, March 2005.

[35] Electrical Supply Board, *"ESB Networks Ltd, Statement of Charges",* September 2014.

[36] EuroTransport, *"Alstom Delivers the First Citadis Tramset to the Greater Dijon Urban Area",* January 2012

[37] The Community of European Railway and Infrastructure Companies, *"Public Hearing at the European Parliament"*, 2010.

[38] Community of European Railway and Infrastructure Companies, *White Paper"*, 2006.

[39] The European Rail Research Advisory Council, "*Roadmap Evaluating and Prioritizing Future Rail Research",* 2012.

[40] The European Rail Infrastructure Managers, *"Energy meters on Trains"*, November 2010.

[41] Community of European Railways, "*Rail Transport and Environment, Facts and Figures",* June 2008.

[42] Living Rail, *"Wind Energy to Power the rail network"*, September 2008, available at; www.livingrail.com

[43] Guardian Press Release, "Belgian Railway", Available at http://www.guardian.co.uk/environment/2011/jun/06/tunnel-solar-belgium-rail, Accessed August 2012.

[44] Community of European Railways, *"Railway Safety Regulations",* March 2008.

[45] Department of Communications, Marine and Natural Resources, "*Delivering a Sustainable Energy Future for Ireland",* 2007.

[46] Richard Barrero, et al, *"Energy Savings in Public Transport",* September 2008.

[47] Piyush Itankar, *"Study of Super-capacitors (Construction of Super-capacitors)",* accessed May 2012.

[48] Joeri Van Mierlo, et al, *"Improving Energy Efficiency in Public Transport"* September 2008.

[49] Jisheng Hu, *"The design of regenerative braking system in light rail vehicle energy-storage Ultra – capacitor",* September 2008.

[50] Ticket to Kyoto, *"WP2B Energy Recovery",* March 2011.

[51] Luis Mir, et al, *"A Super-capacitor based light rail vehicle: System design and operational modes",* September 2009.

[52] J.G Yu, *"Computer simulation of wayside energy storage substations in DC traction power systems",* February 2010.

[53] Local Government Association of South Australia, *“Sustainable Public Lighting, Technical Feasibility Report”,* August 2009.

[54] Wan Norsyafizan, et al*, “Energy Efficient Lighting System Design for Building”*, January 2010.

[55] Guan, et al, *“Design and implementation of LED daylight lamp lighting system”*, 2008.

[56] European Commission, *“European’s Satisfaction with Rail Services”,* December 2013.

[57] Olivier Neu, *“Research on Energy Efficient Transport – the Luas case study,* September 2011.

[58] EnergyPlus software documentation, Available at, https://energyplus.net/documentation, Accessed October 2015.

[59] Gabriel Haller, *“Thermal Comfort in Rail Vehicles”*, September 2006.

[60] Gregor Richter, *“RailVolution”,* Volume 10, No 6, 2010.

[61] Kawasaki, *“High Speed Rail Seminar”,* Washington DC, January 2009.

[62] Bombardier, *“FLEXX Urban Bogies Easy access in the city”*, available at http://www.bombardier.com/en/home.html, accessed May 2012.

[63] Alstom, *“What will your Citadis Be”,* accessed May 2012.

[64] ABB, *“Traction Motors”*, available at http://www.abb.com/product/us/9aac157695.aspx, Accessed May 2012.

[65] Railway Technology Journal, *“Tenerife Light Rail System, Spain”*, 2010.

[66] Zhe Chen, et al, *“A Review of the State of the Art of Power Electronics for Wind Turbines”*, October 2009.

[67] Ticket to Kyoto, *“Reducing carbon, energy and costs in public transport”,* 2014.

[68] Rail Research UK, *"Human Factors in Railway Systems",* August 2003.

[69] Rail Safety and Standards Board, *"Understanding Human Factors, a guide for the railway industry",* June 2008.

[70] Hartley, *"New Technologies and Exiting Driving Cabs – the Human Factors of Successful Integration",* Interfleet Technology LTD, United Kingdom, 2012

[71] Deutchse Bahn, *"Energy Efficient Driving",* November 2008.

[72] Intelligent Energy Europe, *"Inventory of Energy Efficiency Good Practices For Railway"*, 2010.

[73] Intelligent Energy Europe, *"Energy Efficiency Driving For Train Drivers",* 2010.

[74] Litman, "*Evaluating Rail Transit Benefits: A Comment*", Victoria Transport Policy Institute, Victoria, British Columbia, Canada, November 2006.

[75] Swanson et al, "*Light Rail Transit Systems*", IEEE Vehicular Technology Magazine, June 2010.

[76] Fox, "*LRT V Buses: Why Portland Chose Light Rail*", www.tramnews.com, October 2009.

[77] Alstom Tramway Club Conference, Barcelona, March 2015.

[78] Alstom Tramway Club Conference, "*Presentation on Casablanca Light Rail System*", Barcelona, March 2015.

[79] Railway Technology Journal, *"Barcelona, Spain"*, 2010.

[80] Alstom Transport, *"Generating Sustainable Mobility",* 2010.

[81] Alstom Transport, "*HESOP Press Release"*, Available at http://www.alstom.com/transport/products-and-services/rolling-stock/citadis-tramways/Animation-3D-HESOP-VA/, Accessed July 2012.

[82] Site visit and meeting with Patrick Le Buff, Gent Belgium, May 2012.

[83] Business Green Press Release, *"Dutch wind turbines to power electric trains",* Available at, http://www.businessgreen.com/bg/news/2345334/dutch-wind-turbines-to-power-electric-trains, accessed May 2014.

[84] Dr. Michael Steiner, et al, *"Energy Storage System on Board of Railway Vehicles",* 2005.

[85] Railway Gazette, "*High-speed flywheels cut energy bill*", April 2011.

[86] Luas Operational Structure, courtesy of Transdev, 2012.

[87] Luas Route Map, available at www.rpa.ie /en/luas_lines/Pages/default.aspx , Accessed 2013.

[88] Luas Track and Gradient Profile Measurements, courtesy of Transdev, 2011.

[89] Luas Timetable and Operational Hours, courtesy of Transdev, 2011.

[90] Luas Electrical Infrastructure Specifications, courtesy of RPA, 2011.

[91] Luas Citadis Vehicle Specifications, courtesy of Transdev, 2012.

[92] Mark Cullen, *"Luas tram electrical schematic",* courtesy of RPA, 2012.

[93] Alstom Transport, Motor Bogie Specification, courtesy of Alstom, 2012.

[94] Alstom Transport, Regenerative Braking Testing Documents, courtesy of Alstom, 2012.

[95] Alstom Transport, Climatic Control Specifications, courtesy of Alstom, 2012.

[96] EN 14750, *"Railway Applications –Air Conditioning for Urban and Sub-Urban Rolling Stock",* 2006.

[97] Alstom Transport, Interior and exterior Lighting Specifications, courtesy of Alstom, 2013.

[98] Alstom Transport, Auxiliary Energy Specifications, courtesy of Alstom, 2013.

[99] Luas Substation Design Drawings, courtesy of RPA, 2013.

[100] Meter Registration System Operator, Luas Energy Consumption Data, 2013.

[101] Luas Stop Electrical Configuration Drawing, courtesy of RPA, 2013.

[102] Luas Low Voltage Energy Consumption, Courtesy of Transdev, 2012.

[103] Luas Depot Electrical Configuration Drawings, courtesy of RPA, 2013.

[104] Tram Static Energy Consumption Testing, 2011.

[105] PS Scada Depot Energy Consumption Data, 2012.

[106] Luas Cross City, *"Bringing The City Together",* Project Information, June 2013.

[107] Information from Traffic Event Database, courtesy of Transdev, 2013.

[108] Luas Tram Heating and Ventilation Testing, 2012.

[109] Alstom Transport, Original Engineers Maintenance Manual, courtesy of Alstom, 2012.

[110] Luas VMC-1 Annual Maintenance Plan issue 29, courtesy of Transdev, 2013.

[111] Alstom Transport, Dublin Citadis VMC-1, Maintenance Cross Reference, courtesy of Transdev, 2013.

[112] Luas Tram Mileages, courtesy of Alstom, 2013.

[113] Alstom Transport, "*Rolling Stock Modernization, Engineer a New Life for your Fleet*", 2013.

[114] Irish National Meteorological Service, Temperature data 2012.

[115] Luas Automatic Vehicle Location System, operational manual, courtesy of Alstom, 2013.

[116] EN 13272:2001 *"Railway applications, Electrical lighting for rolling stock in public transport systems"*, March 2011.

[117] Phillips, Product Guide, *"Master Led tube GA110 1200mm 19W 840 I ROT".*

[118] Luas exterior lighting list, courtesy of RPA, 2013.

[119] Luas Cookstown Lighting Trial Data Sheet, courtesy of RPA, 2013.

[120] Luas Depot Lighting Trial Data Sheet, courtesy of Transdev, 2013.

[121] Enercon, *"Wind Turbine Specifications",* 2012.

[122] Gamesa, *"Wind Turbine Specifications",* 2012.

[123] Irish Statute Book, *"Wind turbine bill",* 2012.

[124] Luas Depot As Built Drawings, courtesy of Transdev, 2015

[125] Electricity Supply Board, *"Maximum Import Capacity – Statement of Charges Document*", 2013.

[126] Luas MIC levels and charges, courtesy of Transdev, 2013.

[127] PS Scada Luas Energy Consumption Data, 2013.

[128] Commission for Energy Regulation, *"Public Service Obligation Levy 2015/2015",* June 2014.

[129] Powersoft Tram Energy Meters Data Sheet, courtesy of Transdev, 2013.

[130] Luas Tram Regenerative Power Testing, 2013.

[131] Kyoungmin Son, et al, "*Line voltage regulation of urban transit systems using supercapacitors*" 2009.

[132] Alstom E-Mapping Trial Data Sheet, courtesy of Alstom, 2013.

[133] Luas Master Controller Figure, courtesy of Transdev, 2013.

[134] Luas Optimal Driving Style Testing, 2012.

[135] PS Scada, Luas Depot power Consumption, 2013.

[136] Function of MRSO, available at www.mrso.ie/about, accessed 2013.

[137] Quoted Charges from Transdev Energy Tender, 2015

MODIFICATION OF LUAS HEATING AND VENTILATION SYSTEMS TO REDUCE ENERGY CONSUMPTION

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Abstract

Luas is a state of the art light rail system operating in Dublin Ireland. Being electrically powered, energy is a major operating cost for Luas. One component of rolling stock identified by this research that consumes a disproportional amount of energy is that of the heating and ventilation systems. The heating and ventilation systems fitted to Luas vehicles consume as much as 60% of total vehicle power, and under certain conditions can consume more than that of the traction motors. This paper explores solutions to reducing the energy consumption of Luas heating and ventilation systems. The identified software modifications and hardware installations proposed by this research have been estimated to save over 1,400,000 kWh, 7% of total Luas energy consumption. Based on the current average industry price of €0.12 per kWh, this saving equates to almost €170,000 per year.

Transport systems are not immune to the economic downturn seen throughout the Europe Union. With decreasing passenger numbers, operators are faced with reduced revenue streams, which could lead to reduced services or possible job losses. To avoid such action, operators must reduce their operating costs adequately. Heating and ventilation systems provide passengers with a controlled, fresh, temperature-regulated air supply to ensure maximum comfort. Light rail systems are arguably one of the most difficult transport modes in which to regulate air temperature and quality, due to their short trip distances with a high number of stops.

Each Luas vehicle has three heating and ventilation units. The total rated power of the three systems is 60 kW, power is supplied by way of 750 V DC direct from the overhead catenary supply. Each unit is controlled by a self-contained control unit where in all eventualities, the system endeavours to achieve a variable interior set point between 14 °C and 20 °C. The system is set up to automatically start once the vehicle is prepared (switched on) and will remain on (temperature depending) until the vehicle is de-prepped (switched off).

Testing of the system, recorded a maximum consumption of 60 kWh at an operating temperature of 2 °C. Contrastingly a test conducted at 19 °C the consumption was 3 kWh. Detailed analysis of Luas operations indicates that on average 30% of the time Luas trams are in operation, is not actual passenger service. However the heating and ventilation systems are operational during these periods. Automatically disabling the systems during these non-passenger periods would reduce energy consumption significantly, while not adversely affecting passenger comfort.

To achieve this objective, three modifications have been identified. The first two will automatically disable the heating and ventilation system while operating in periods of non-passenger service when the vehicle is in traction and while the vehicle is stable in the shunt (end of line). The third modification will reduce the set point profile, the system endeavours to reach. The paper describes in detail the software modifications and hardware installations required to roll out these modifications across the Luas fleet.

I. Introduction

Energy is a significant cost for operators of electrically powered rail systems. One component of rolling stock energy consumption is that of climate control systems. Heating, ventilation and air conditioning systems may consume as much as 60% of the total power of light rail vehicles [1]. Heating, ventilation and air conditioning systems provide passengers with a controlled air supply to ensure maximum comfort. These systems deliver a temperature-regulated air supply to the passenger compartments of the light rail vehicles. Such systems should also provide a fresh airflow, which must comply with the European Standards EN 14750-1 of 2006 for rolling stock [2].

With a recent fall in passenger numbers across the European rail industry, operators are striving to increase passenger satisfaction and comfort to make rail transport a viable alternative to the passenger car [3]. One aspect of passenger satisfaction is thermal comfort within light rail vehicles, determined by the air quality. Haller [4] describes thermal comfort as a perception by passengers that the surrounding air is of ideal temperature, humidity and pressure. Heating ventilation and air conditioning systems are installed to achieve optimal thermal comfort, but come at a cost to transport operators.

II. Modeling

Light rail vehicles are arguably one of the most difficult transport modes in which to regulate air temperature and quality. These systems are characterized by their short trip distances with a high number of stops. As a consequence, vehicle doors are constantly opening resulting in the passenger compartment air being recycled at regular intervals. Luas operations show the heating and ventilation system, energy consumption being four times its design allowance [5]. The Luas Red Line is a 16.5 km track section. There are 26 stops along the line from Tallaght to the Point stop. Alstom Citadis 401 style vehicles are operated on the Luas Red Line. The vehicles are 40 meters in length and have an occupancy rating of 6 people per meter squared (ppm^2) [6]. Each vehicle consists of five passenger compartments M1, NM, CC, NP and M2 as described in figure 1 below.

The passenger compartment has a total area of 81.3 m^3 and a total volume of 179 m^3 [6]. According to research by Neu [7] the estimated air leakage area of Luas passenger compartments is 2144 cm^2. The average U value (overall heat transfer coefficient) of the glass doors and windows within the passenger compartment is 155.68 (W/m^2-K). The average R value (thermal resistance) of the surrounding structure is 7.28 (W/m^2-K). Comparing these U and R values and the overall insulation envelope of Luas to the values seen in Chow [8], a study of a Hong Kong passenger rail system, the thermal insulation of Luas vehicles is significantly lower. In addition, Luas vehicles stop on average, less than every 3 minutes where the saloon air is almost completely recycled with outside air [9]. As a direct result of this, maintaining the desired interior set point temperature by way of a heating and ventilation system can consume significant amounts of energy and prove inefficient.

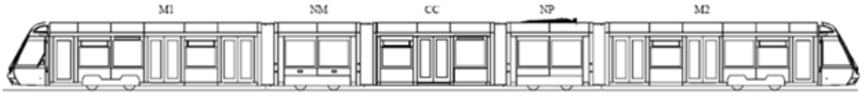


Figure 1: Citadis 401 Style Tram Vehicle Layout

With an average temperature range not exceeding 20 °C in Ireland [10], there is no requirement for an air conditioning module on Luas vehicles. Each vehicle has three heating and ventilation systems installed. The units are located on the roof sections of M1, CC and M2 cars. Each heating and ventilation system consist of a self contained unit which houses a fresh air inlet of 1.32 m^2, a resistor heater eliment, a ventilation fan, temperature sensing probes and a control unit, shown in figure 2. The electric resistor heater eliments have a rated power of 18 kW, power is supplied by way of 750 V DC direct from the overhead catenary supply. The heater elements are controlled by a proportional integral derivative regulator connected to the internal control unit [11].

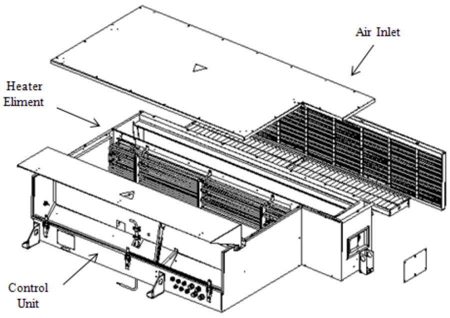


Figure 2: Luas Heating and Ventilation Unit

A fan located within the base of the unit provides ventilation. The fan is powered by an asynchronous motor, which has a power output of 510 W at a Rated speed 1400 r/min allowing for a max Airflow of 3600 m³/h. Both the fresh and recirculated air inlets are controlled by a damper, which has a torque value of 4 Nm and a max opening/closing time of 35 seconds. This damper regulates the flow of both fresh and re-circulated air, and can rotate the ratios between both. Thermostatic temperature probes located, inside the passenger saloon and externally relay temperature signals to the control unit [11]. The heating and ventilation system is controlled by a self-contained control unit. In all eventualities, the system endeavors to achieve a variable interior temperature set point. This set point is determined by a set point formula, which is influenced by the exterior temperature. The set point formula is 20 ºC + 0.25 x (STN – 17ºC) where STN is the temperature of the fresh air at the inlet [12]. Figure 3 describes the set point profile. The heated air supplied by the system is fed into a main duck located on the roof of the interior passenger compartment [11].

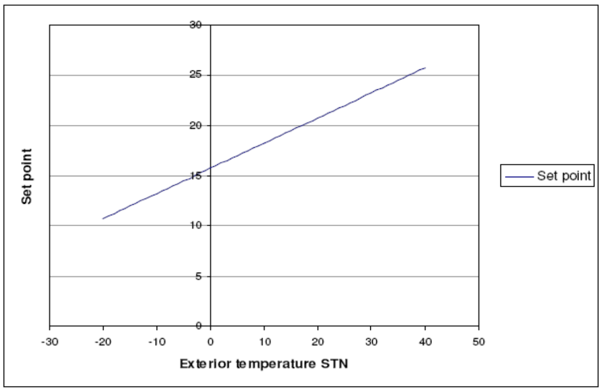


Figure 3: Set Point Profile

There are 3 functional settings to which the system will operate as described in table 1 (STI refers to the interior set point).

Operation	Temperature	Flap Position	Air Flow Rate (m3/h)	Fresh Air Rate (ms/h)	Recirculated Air Rate (ms/h)
Heating	When STI < Set point – 3 ºC	Closed	3600	0	3600
Heating	When Set point – 3 ºC < STI < Set point + 3 ºC	Partially Open	3600	900	2700
Ventilation	The heating resistor is switched off and the air fresh inlet is at maximum.	Fully Open	3600	3200	400

Table 1: Heating and Ventilation Operation

III. Consumption Analysis

Based on the power ratings of the Luas heating and ventilation system components, the maximum consumption per vehicle is 60 kW. However it would be assumed that the actual consumption would be much less than this, especially during summer operations. Tests were performed on the Luas Red Line where, on average an in-service round passenger trip along this route takes 120 minutes [9]. Testing took place during winter and summer months with the temperatures and energy consumption recorded. Table 2 outline some of the results acquired [12].

Test	Day	Time of day	Duration of test (Mins)	Km travelled (Km)	Heater Consumption	Auxiliary Consumption	Temperature (oC)	Heater Consumption (kWh/hr)
Test 1	Sunday	07:14	108	32.4	83	2.8	6	46.1
Test 2	Monday	09:07	121	32.4	96	2.8	9	47.5
Test 3	Tuesday	11:17	106	32.4	45	2	11	25
Test 4	Wednesday	13:10	113	32.4	39	1.9	12	21.7
Test 5	Monday	14:30	120	32.4	46	2	13	23
Test 6	Thursday	01:56	92	32.4	105	2.8	2	68.1
Test 7	Thursday	03:30	93	32.4	102	2.8	2	65.8
Test 8	Friday	11:12	115	32.4	23	1.5	12	12.1
Test 9	Saturday	17:20	121	32.4	3	1	19	1.5

Table 2: Testing Results

From the testing results above, it is clear to see the wide range of energy consumption relative to the external temperatures of operation. With a maximum consumption of 60 kW per tram, test number 6 recorded a max consumption at an operating temperature of 2℃. Contrastingly, test number 9 returned results of 3 kWh where the external temperature was 19℃. From these tests, it is clear that seasons and operating conditions have a great effect on the energy consumption of these systems. The percentage of time the heating and ventilation systems are activated on heating mode can be determined from these tests. [12]. Table 3 indicates these percentages relevant to external temperatures.

External Temperature (℃)	Heating Time (%)
<3	100
4-7	70-90
8-11	50-70
11-15	20-50
15>	0-10

Table 3: Heating Consumption Temperatures

IV. Luas Operations Analysis

An analysis of fleet operations indicates the hours of service operated by Luas. Table 4 indicates the hours of service currently provided by Luas [9].

Green Line Operational Hours									
	In Service	Lay Over	Pull In / Out	Preperation	Total	Total OOS	% OOS to In-Service	Total No of Vehicles	Average Hours OOS per Vehicle
Weekday	189:21:00	34:13:00	06:14:00	07:20:00	237:08:00	47:47:00	25.2	19	2:30:54
Saturday	137:10:00	32:16:00	04:46:00	03:40:00	177:52:00	40:42:00	29.7	11	3:42:00
Sunday	101:02:00	22:46:00	04:38:00	02:40:00	131:06:00	30:04:00	29.8	8	3:45:30
Red Line Operational Hours									
	In Service	Lay Over	Pull In / Out	Preperation	Total	Total OOS	% OOS to In-Service	Total No of Vehicles	Average Hours OOS per Vehicle
Weekday	329:57:00	60:22:00	12:27:00	11:12:00	413:58:00	84:01:00	25.5	27	3:06:42
Saturday	137:10:00	32:16:00	04:46:00	03:40:00	177:52:00	40:42:00	29.7	21	1:56:17
Sunday	185:09:00	52:41:00	08:28:00	06:49:00	253:07:00	67:58:00	36.7	17	3:59:53

Table 4: Luas Operational Hours

i. “In service” represents the actual hours the Luas fleet is in passenger service.
ii. “Lay Over” represents the total hours Luas vehicles spend idle at the end of line (shunt area), waiting to depart on the next service.
iii. “Pull In/Out” represents the time taken to exit the depot before going into passenger service and return to the depot after passenger service.
iv. “Preparation” represents the time taken by the Luas fleet to prepare tram vehicles, and complete pre departure checks before departing into passenger service.

On weekday operations over both lines, 25% of the time Luas trams are in operation is in fact not actual passenger service. As mentioned above, during this time tram vehicles are fully prepped and functional and as a result the heating and ventilation systems are automatically activated (consumption will be temperature depending). On Saturday and Sunday operations, this non-passenger service time increases to 30% on both lines.

V. Climate Analysis

Ireland's maritime climate is influenced by the Atlantic Ocean and a Polar front that exists around the country during winter months. Winters are cool and generally windy and summer months are mostly mild. According to the Irish Met office, the number of days with an air temperature below 0 ℃ in Dublin is 10 per year and the average temperature is 10 ℃. Table 6 indicates the month average temperatures for the Phoenix Park weather station, the closes weather station to the Luas Red Line [10].

Average Temperature for Previous 12 Months Dublin											
Aug	Sep	Oct	Nov	Dec	Jan	Feb	Mar	Apr	May	Jun	Jul
13.5	14	11.8	9.7	5.8	6.1	6.6	8	6.6	9.8	12.7	14

Table 5: Dublin Average Temperatures

VI. Proposed heating and ventilation system modification

There are a number of potential modifications, which will result in reduction of energy consumption associated with the Luas heating and ventilation system. Because of the above mentioned results, the decision was taken to propose modifications that would automatically disable the system in periods of non-passenger operations. These modifications would result in vast energy savings, while not adversely affecting the operation of the heating and ventilation system while passengers are on board. Three modifications have been identified, these include;

i. Disabling the heating and ventilation system while operating in periods of non-passenger service (When in traction).
ii. Disabling the heating and ventilation system while stable in the shunt.
iii. Reduce the set point temperature profile of the heating and ventilation system.

Depending on external temperature conditions, the consumption of Luas heating and ventilation systems can differ greatly, from a minimum of 1 kWh to a maximum of 60 kWh. Table 6 details the energy consumption savings that could potentially be achieved across both Red and Green lines with the above mentioned modifications.

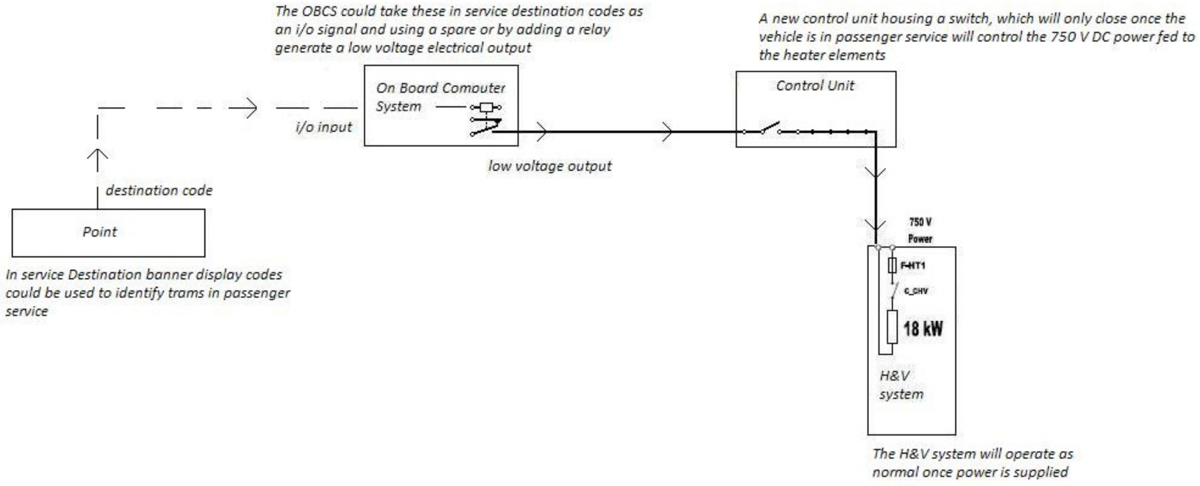
	Total out of service Consumtpion 2012 (kWh)	Potential Total Saving (kWh)	Potential saving (€) (@0.12)	Potential Total Saving (€)		Total out of service Consumtpion 2012 (kWh)	Potential Total Saving (kWh)	Potential saving (€) (@0.12)	Potential Total Saving (€)	Potential Fleet Saving
LUAS RED LINE	106367	**910,126**	€12,764	**€109,215**	**GREEN LINE**	59005	**509,227**	€7,081	**€61,107**	**€170,322**
	99587		€11,950			55639		€6,677		
	78790		€9,455			44602		€5,352		
	102468		€12,296			56942		€6,833		
	80555		€9,667			44817		€5,378		
	75869		€9,104			43055		€5,167		
	46674		€5,601			25886		€3,106		
	47121		€5,655			26219		€3,146		
	43930		€5,272			24855		€2,983		
	47121		€5,655			26219		€3,146		
	77630		€9,316			43270		€5,192		
	104014		€12,482			58718		€7,046		

Table 6: Potential Energy Savings of Modification

Modifications to disable the heating and ventilation system have the potential to save in the region of 1,419,353 kWh per year. This is an average figure calculated over a twelve month period. Savings would realistically be greater in winter months and less during summer periods.

The first modification proposed deals with disabling the heating and ventilation system while operating in periods of non-passenger service, but where the tram is in traction. In order to disable the heating and ventilation system during these periods a number of options were explored. The following modification has been identified as the most simplistic, resulting in the least invasion to Luas vehicles. The modification process is as follows;

Passenger service vehicles automatically display a set destination on the external display banner. This is achieved through the automatic vehicle location system (AVLS), which uses specific service files to determine what service a vehicle is operating and where its destination is. Using ground loops the AVLS can detect when a vehicle is at the designated stop to begin passenger service. Once this loop is detected by the AVLS the external display will automatically display the vehicles destination. Each destination display will have a unique coding within the specific service file. This coding can be used to determine when a vehicle enters passenger service. Each unique coding can be flagged within the service file. Once a flag is identified an input / output signal will be generated and sent to the vehicles on board computer system (OBCS). This connection and communication is already in place on Luas vehicles for other functions and therefore will only have to be modified to accommodate this new process. The OBCS will take this input/output signal once the vehicle enters service and the destinations are displayed, and by adding a new relay generate a low voltage electrical output. This output will then be hard wired to a new control unit. Within this new control unit will be an on/off switch. On command the switch will close sending power to the heating and ventilation system once in passenger service. The system will then work as originally designed. Once the tram finishes service the AVLS will automatically revert back to "not in service", the switch will then open cutting power to the system. This modification would result in no power being fed to the heating and ventilation system when the tram is not in passenger service. These times equate to 76 hours per week across both lines. Figure 4 describes the modification in schematic form.



The OBCS could take these in service destination codes as an i/o signal and using a spare or by adding a relay generate a low voltage electrical output

A new control unit housing a switch, which will only close once the vehicle is in passenger service will control the 750 V DC power fed to the heater elements

In service Destination banner display codes could be used to identify trams in passenger service

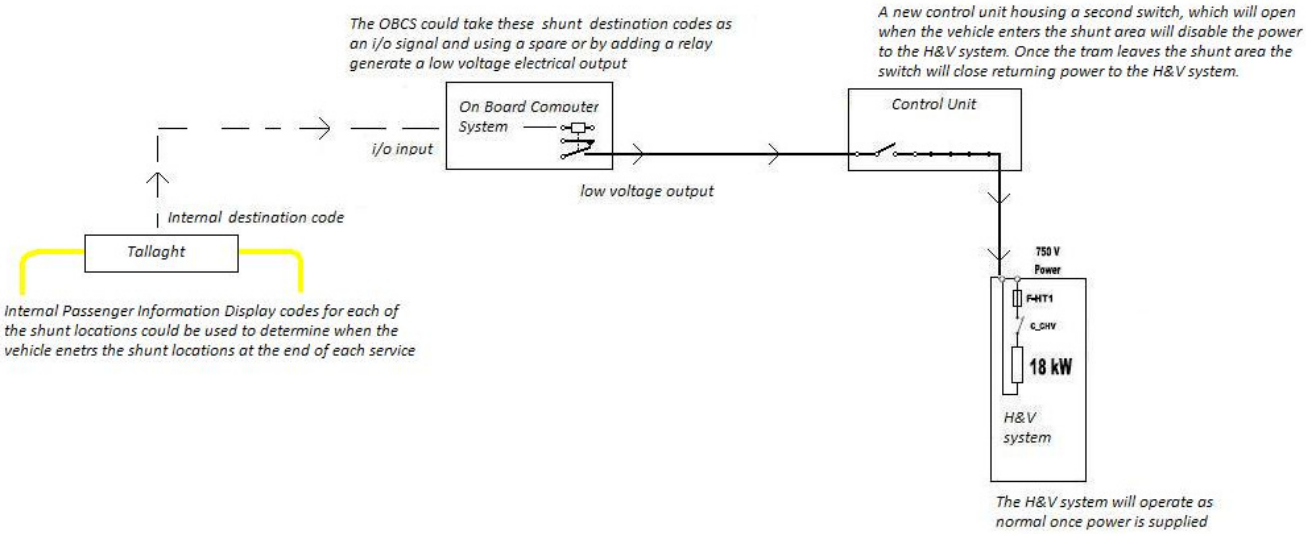
The H&V system will operate as normal once power is supplied

Eoghan Sweeney 25/09/2012

Figure 4: Modification Schematic

To disabling the heating and ventilation system while stable in the shunt a second modification is required. The shunt is the area at the end of each line. Vehicles can spend anywhere from 2-10 minutes in the shunt waiting to depart on their next service as per the timetable. While vehicles are in the shunt, the tram is prepped (switched on) and effectively in service. As a result, the AVLS destination displays are activated and therefore, the above modification will not disable the heating and ventilation system during these periods. A second modification has been proposed for shunt periods. The modification process is as follows;

The automatic vehicle location system (AVLS) communicates with ground loops located around the Luas system. Once a vehicle passes over these loops the AVLS can locate the vehicle anywhere on the line based on loop identifications. Using this system, the destination each vehicle is about to enter is identified by the AVLS and the destination name is displayed on the internal passenger displays. Each destination display will have a unique coding within the service file. This coding can be used to determine when a vehicle enters the shunt locations. Each unique coding for all the six shunt locations can be flagged within the service file. Once the flag is identified an input/output signal will be generated and sent to the vehicles on board computer system (OBCS) similar to the above modification. This connection and communication is already in place on Luas vehicles and therefore will only have to be modified to accommodate this new process. The OBCS will take this input/output signal once the vehicle enters the shunt locations. By adding a new relay to the OBCS, a low voltage electrical output will be generated. This output will be hard wired to the new control unit as mentioned before. Within this new control unit will be a second switch, located after the first switch, in series. On command the switch will open cutting power to the heating and ventilation system. The system will now not be fed power while in the shunt locations. Once the vehicle leaves the shunt locations the AVLS, through ground loops will recognise the vehicle has left and the switch will close again, sending power back to the heating and ventilation system. This modification would result in no power being fed to the system while stable in the shunt areas awaiting the next departure. These periods equate to 451 hours per week across both lines. Figure 5 describes the modification in schematic form.



The OBCS could take these shunt destination codes as an i/o signal and using a spare or by adding a relay generate a low voltage electrical output

A new control unit housing a second switch, which will open when the vehicle enters the shunt area will disable the power to the H&V system. Once the tram leaves the shunt area the switch will close returning power to the H&V system.

Internal Passenger Information Display codes for each of the shunt locations could be used to determine when the vehicle enetrs the shunt locations at the end of each service

The H&V system will operate as normal once power is supplied

Eoghan Sweeney 25/09/2012

Figure 5: Modification Schematic

The original set point profile for the Luas heating and ventilation systems resulted in the system endeavoring to reach an internal temperature of at least 12 ℃. From testing it has been found that during winter operations the heating and ventilation system fails to reach the set point as a result of poor insulation and regular door openings. As a consequence the system is in heating mode 100% of the time once the external temperature drops below ~4 ℃. Therefore the set point profile is inefficient for Luas operations. In order to reduce the energy consumption associated with the system, the set point formula can be modified to reduce the period of time the system is activated and heating. The modification process is as follows;

The set point profile for Luas heating and ventilation system is determined by a fluid formula, which incorporates the external temperature. The formula is 20 ºC + 0.25 X (STN – 17ºC), where STN is the temperature of the air at the inlet. This produces a set point profile as displayed in figure 3 above. This formula is set within the control unit of the heating and ventilation system and can be simply modified by connecting into the control unit at source. By modifying this formula to **20 ºC + 0.25 x (STN – 50ºC)** a more realistic and efficient set point profile is achieved.The energy consumption associated with the system will be reduced, as the period of time the system is activated in full heating mode will be reduced. Note that the 3 functional settings to which the system operates will remain as designed and indicated in table 1 above. Prior to installation, it is difficult to quantify or estimate the saving such a modification will make. As Luas vehicles operate at different times of the day with different passenger loads and at variable temperatures the savings will differ from vehicle to vehicle and from day to day. However, this modification will almost certainly reduce the amount of time the system is on full heating mode, as the internal temperature will be achieved in a shorter time span. Exact energy consumption savings will only be known after the trial period has taken place.

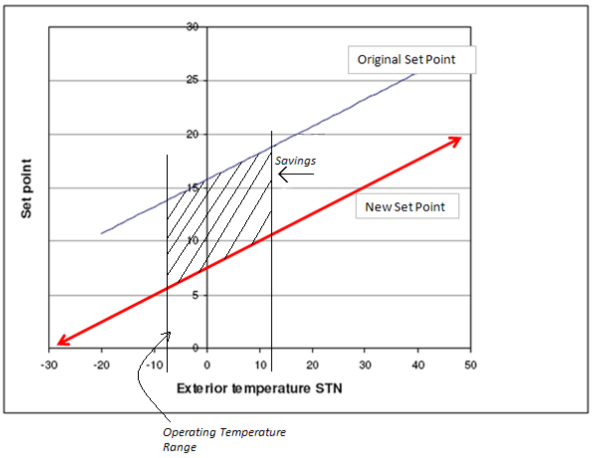


Figure 6: Schematic of set point formula modification

VII. Conclusion

Luas heating and ventilation systems can consume in excess of 60% of vehicle power in winter months, this is 4 times its designed power allowance. In some tests during this research, the consumption of the heating and ventilation system was in fact greater than that of traction motor power. Further analysis the system revealed the inefficient operation of the heating and ventilation system as installed. A conservative estimation found that some 1,419,353 kWh of energy could potentially be saved by modifying the system. To achieve this 3 modifications have been proposed, to disable the system while vehicles are not operating in passenger service and also to modify the set point formula resulting in a more efficient system. The next step in this research is to trial these modifications on a Luas tram. Energy consumption values will be recorded and analyzed for a period of at least six months, incorporating the winter seasons. Future papers will detail the trial period results and include a cost benefit analysis, and return on investment for the project.

References

[1] G. Richter, Eco Tram Research Project: How much energy is used by the HVAC of a tram?, Vienna University of Technology, 2010.

[2] European Standard, BS EN 14750-1-2006, 2006.

[3] Railway Passenger Transport Statistics - Quarterly and Annual Data, October 2011.

[4] G. Haller, Thermal Comfort in Rail Vehicles, Rail Tec Arsenal, 2006.

[5] Luas Electrical Design Drawings and Documents, Courtesy of Transdev, Accessed 2012.

[6] Manufacturer's General Functional Specification, CITADIS 401, Alstom, Accessed 2008.

[7] O. Neu, Research on Energy Efficient Transport – The LUAS Case Study, UCD, 2011.

[8] Chow, W.K. and Yu, P.C.H., Simulation on Energy use for Mechanical Ventilation and Air-Conditioning (MVAC) Systems in Train Compartments, Elsevier, 2000.

[9] Luas Timetable Information, Courtesy of Transdev, 2012.

[10] Irish Met Office, www.met.ie, Accessed 2012.

[11] Constructor Detailed Functional Specification, Climatic Comfort System, Alstom, Accessed 2012.

[12] Luas energy consumption testing performed on tram number 3010, 2012.

Energy savings in Light Rail Transit

Summary and conclusions of Dec. 2013 UITP seminar

On 4 December 2013, some 50 experts from 11 countries including Malaysia, attended the Seminar "Energy efficient Light Rail" in Brussels.

Introduction

Energy represents **15 to 20% of the operation expenditures** of a light rail network. The last years have seen **dramatic price increases** of electricity in many places. In Paris, kWh increased by 68% between 2004 and 2012; In Brussels by 41% between 2007 and 2012, i.e. an **average annual increase of no less than 8%**! With global energy consumption predicted to grow by 56% between 2010 and 2040, it is rather unlikely to expect any tension release on the electricity market. Therefore, if operation of rail transport system is to remain cost-effective, all options to save energy and avoid waste have to be explored and exploited.

In this context of further escalation of kWh price, the **return on investment** discussion is taking a new dimension. Assessment of investments into energy saving measures and technologies and expected payback period are more likely to deliver positive evaluation, or will require less public support to be viably implemented.

The discussions highlighted that efforts in energy efficiency should be **carefully-thought business decision**, not a love story with technologies. To put it bluntly, operators are not interested to save energy, nor emissions. They want to save money!

The seminar looked comprehensively into both technology and "soft" options, and was considering "quick wins from low hanging fruits" (with a typical ROI of 1 year), as well as longer-term investments.

Soft measures

The measures discussed included: full de-energisation of LRVs in parking mode (lowering pantograph) overnight; eco-driving programmes and trainings; Optimized HVAC temperature setting in LRVs, stations and workshops; Acting on lightning in stations and workshops; Time-tabling optimization...

Studies performed by the Light Rail Committee in 2011 show that complete **de-energisation of LRV in parking mode** could help achieve non negligible energy savings. Many operators stable their LRV connected to the grid overnight. Thorough measurements in Barcelona have identified that complete de-preparation of trams stabled in yards can save about 65,000 kWh per vehicle per year.

Heating-Ventilation-Air-Conditioning (HVAC) is a major energy consumer. Auxiliaries can represent as much as 40-45% of total LRV energy consumption (see fig. 1). Detailed analysis performed in Berlin has shown that HVAC alone (in driver cab and passenger saloons) was responsible for 60% to 85% of this consumption, depending on season, far above any other single auxiliary item (lighting, CCTV, ticketing, PA system, traction fans and coolers, sanders etc..). Adjustments and monitoring of HVAC can therefore yield significant consumption impact. For instance, decreasing train temperature from 18 to 15°C in Paris RER allows saving 40,000 kWh per train annually. Cooling in hot days is an important comfort feature for passengers. However, with doors opening every few minutes, maintaining a constant given temperature, say at 20°C is not very efficient. As passengers travel for rather short periods of time, it is more important to address their perception of cooling and to adopt an operation policy of delta rather than given temperature (e.g. external temperature -3°C). This could also be achieved by less energy consuming "cooled ventilation", or by implementing shielded or double glazing, instead of full-fledged AC. Review of temperature setting in stations and depots can also be easily adopted with minor impact on customer and worker satisfaction. An energy audit carried out in a tram depot in Bobigny (Paris) concluded that at least 15% energy saving was achievable on HVAC and lighting.

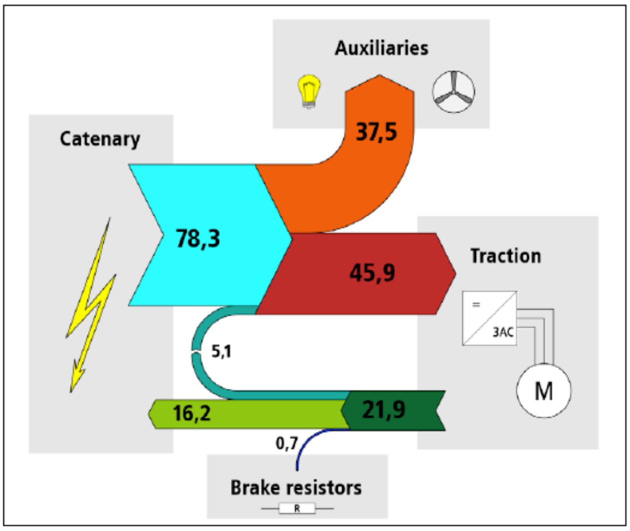
Eco drive savings potential are estimated around 10%. This can be achieved at the detriment of running time and commercial speed, but in much lower proportion (+3%). It was also argued that dwell-time optimization could offset this running time penalty. LRT operators should be well advised to carry out awareness campaigns and training of their drivers. Cab instrument showing in a very simple way and in real time traction consumption would also be very useful tools to support drivers in their duties. However, it seems that strangely enough, such instruments are not (yet) available on the market.

Operation planning and time tabling has a critical influence on energy consumption: Provided that the track is sufficiently segregated to avoid disruption by general traffic and to keep headway regularity along the day, it is possible to design a time-table that synchronizes train braking and departing on the same sub-station. More importantly, time-table design should avoid simultaneous departure of several LRVs in order not to strain the substation. Of course this is more challenging to achieve with LRV running on-sight, than in ATO-enabled metros, but it is nevertheless worthwhile.

Technology measures and systems

The technologies investigated during the seminar all addressed traction power and more specifically options to improve braking energy recovery and avoid to waste it in braking resistors.

In some companies, investing in energy storage device is not needed nor cost-effective, as they are able to recuperate most braking energy: in Berlin, from a total of 78 kW taken from the catenary, 16 is re-injected successful into the grid and just 0,7 (>1%) is burnt in resistor (see fig. 1). However, not all operators are so lucky, and there is a strong interest for storage devices. A wide range of technologies are available with various degrees of maturity. They can be clustered as stationary or on-board applications.



average power flow in kW, Q01 2013

Stationary systems include flywheels and reversible substations. **Reversible substations** allow sending back surplus electricity to the grid if there is no accelerating tram on the section to absorb it. 2 devices installed in Bielefeld display an excellent 98% efficiency and led to the decision to purchase a 3rd substation. With 2 reversible sub-stations and 1 flywheel, the operator could save 900,000 kWh annually. The payback period is 10 years, reduced to 5 if public support is taken into account.

Since March 2013, Freiburger Verkehrs AG has been testing a **stationary flywheel** in the vicinity of a terminal tram loop, where headways are long and braking energy mostly wasted. This pilot project required an investment of 380,000€, and was partly supported (150,000€) by a regional fund.

The one year test period aims at testing the equipment and demonstrating its economic viability: a threshold of annual energy savings of 250.000 kWh has been computed to reach the objective. To date, results show significant electricity savings, but fail to meet this threshold yet. Further fine-tuning and setting work is required to reach optimal efficiency. In addition, environmental benefits are also investigated (avoidance of 145 Tons of CO2) as well as the acceptance for neighboring residents (noise analysis).

The question is whether in the future, batteries or double layer super-capacitors could be also installed on way-side to avoid additional tare weight on LRVs (that are in turn consuming more and suffer from pay-load penalty – the more tare, the fewer passengers!). The question remained open…

On-board energy storage device: all manufacturers offer solutions such as super caps (SC): Siemens, Alstom designed for 1.2 kWh in SC and 10 years life; CAF, ACR system designed for 4 kWh in SC and 15 in batteries; Bombardier with its MITRAC system designed for 15 years life or traction batteries of 50 kWh designed for 10 years life.

Catenary-free power supply systems (CFP) are actually not energy saving systems *per se*, but as they are increasingly combined with the storage device listed above, manufacturers provided an overview of their developments: in addition to its APS, Alstom also offers CFP with 2 boxes of super caps that allow LRV to run over standard inter-station distance, included in degraded mode. Bombardier presented its induction Primove system with its advantages of being contactless and resilient to any weather conditions. CAF presented its ACR Freedrive system, soon to be implemented in Taiwan Kaohsiung.

Rolling stock procurement

Many operators (if not most?) still procure LRVs with little attention to electricity consumption, although the consumption performance will be of significant impact over the whole life cycle of the asset. The OSIRIS project presented an attempt to design standardized modules that could be used to request comparable energy consumption data from manufacturers. A limited set of modules could be combined by operators to figure out an approximate consumption on their network. This approach was inspired from the SORT method developed by UITP for buses a decade ago and that is a well established practice in bus procurement now. Progress on this methodology will be reported when it is more mature.

Conclusions

Hence, there is no “one-size-fits-all” because prevailing conditions and especially subsidy regimes for investment in “green tech” are different everywhere. It was recognized that there are no small benefits: Any improvement of energy efficiency results from cumulative efforts.

It is important to remember that looking for energy savings is OK, but should not be done at the detriment of passenger comfort. Customer-orientation should remain the priority in trade-offs (Air-conditioning or not? Eco-driving to affect travel time…)

SEAI Awards 2013

Presentation 09 October 2013

“An investigation into options for reducing energy in the operational phase of a light rail system”

Received Benefits

Before reducing energy an organisation must establish where and when energy is consumed.

RESEARCH

+

ON-GOING MONITORING OF ENERGY CONSUMPTION

=

COMPANY LEARNINGS ON ENERGY USAGE AND ENERGY DEMAND

- **Through this we gained an understanding of where disproportional amounts of energy were being consumed, *eg.* Heating & Ventilation (H&V) systems, non-efficient driving styles, old lighting systems, and depot energy.**
- **Having this knowledge allowed us to begin implementing energy reduction initiatives.**
- **Energy related benefits: H&V system modification, Luas depot power management, Luas depot lighting retrofit and establishment of efficient driving techniques.**

The Research benefits are bigger than just energy reduction…

- **Efficient Driving styles increases tram energy efficiency, but it is also better for tram components, safer and more comfortable for passengers. This could result in improving overall customer satisfaction.**

- **Induction lighting provides better working condition for staff (increased lux levels, instant light/no warm up time). This has resulted in better staff satisfaction and productivity in the workshops.**

- **New thinking and knowledge dissemination: opened new ways of thinking in order to reduce energy.**

- **The research demonstrates a successful collaboration between public sector, private sector and an education institution. Not only resulted in increased knowledge amongst Transdev & RPA staff but also can be used by DIT as part of on-going education in the engineering curriculum.**

It is also about PEOPLE…

- **Staff engagement: daily reporting of depot power to key stakeholders; increased awareness about energy consumption amongst staff; quarterly meetings between Transdev, RPA and Alstom.**
- **A project that involves many organisations and employees at all levels:**

Managing Directors & RPA Board
Vehicle Maintenance Co-ordinators
Contracts, Operations, Safety Departments
Alstom technicians, Luas drivers

- **Researcher is now a full time employee within Transdev Dublin.**
- **We will soon be communicating our results to local schools green teams and have also been asked to participate in the SDCC Leap programme.**

Future benefits

Developing eco driving programme for Luas operations will have the potential to be replicated in other light rail operations over the world.

Reducing energy will help us achieving our environmental targets (Luas SD Plan) and reduce CO_2 emissions.

Reinvesting the savings made through energy reduction

Participation in EU research programmes: UITP and OSIRIS

LUASCROSSCITY

Depot power management, efficient driving styles will be implemented as part of Luas Cross City training, Energy efficiency review of Luas Cross City design