Final Report

Life-Cycle Carbon Impact Assessment of the *Celsius* project

Document History

Project name	Life-Cycle Carbon Impact Assessment of the *Celsius* project
Author	Dr Herb Castillo (herb.castillo@futurofirma.com)

Version	Issue Date	Status	Issuer	Comments
d0.1	15th December 2019	*Draft*	Dr Herb Castillo	*1st Draft issued for review by ENW*
1.0	20th December 2019	*Final*	Dr Herb Castillo	*Final version incorporating ENW's comments on draft*

Executive Summary

Introduction

ENW's Celsius project is exploring innovative, cost-effective approaches for managing potentially excessive temperatures at distribution substations, which could otherwise constrain the connection of low carbon technologies (LCTs).

In this regard, the Celsius project has developed methodologies for better understanding real thermal ratings of distribution substation assets and has identified retrofit cooling interventions that can mitigate temperature increases arising from increasing demand, thus unlocking capacity.

The fundamental hypothesis underpinning the Celsius project is that implementation of the Celsius techniques can extend the useful life of key network assets and defer capital-intensive asset replacement.

Specifically, by enabling better understanding of the thermal behaviour of network assets under operation, establishing latent capacity that can be released quickly with no intervention and utilising a range of effective retrofit cooling techniques, Celsius has the potential to delay the replacement of transformers when demand increases.

This potential to extend the useful life of existing assets, in turn presents opportunities for reduced life-cycle carbon impact.

Accordingly, this report summarises the outcomes of a Life Cycle Assessment (LCA) that has been undertaken to estimate the carbon impact of Celsius techniques relative to traditional interventions for addressing thermal increases on the network.

Carbon impact of Celsius at a substation, relative to the traditional interventions

To enable comparison of Celsius' carbon impact to the traditional approach for addressing thermal increases on the network, the carbon impact was first established of the traditional approach – which is to replace the transformer when capacity ratings are deemed to be at risk of being exceeded. To do so, this study drew on analyses done in a previous Electricity North West innovation project, namely the *Smart Street* project, which estimated the carbon impact of replacing a transformer at 3,938 kg CO_2e.

The life cycle carbon impacts of the applicable Celsius techniques were then assessed. In the context of this assessment, the applicable Celsius techniques are the *Thermal Rating Tool (including the monitoring that underpins its application)* and the active *Retrofit Cooling technologies*, i.e., Passcomm CoolFlow DCM and EkkoSense, the application of which also require installation of Celsius' K^eLVN monitoring solution.

It will be noted that Celsius' passive Retrofit Cooling Techniques, i.e., *improving ventilation, painting outdoor transformers, shading outdoor transformers and improved cable backfills,* were deemed out of scope for this assessment. This is due to their low carbon impact and the unavailability of consistent data regarding their impact on transformer capacity. (Further detail on the rationale for their exclusion is provided in section 2 of this report.)

The assessment of the applicable Celsius techniques, estimated the life cycle carbon emissions arising from utilising Passcomm CoolFlow DCM (plus the K^eLVN monitoring solution) at 75 kg CO_2e and from EkkoSense (plus the K^{e}LVN monitoring solution) at 108 kg CO_2e. The emissions from using the Thermal Rating Tool was estimated at 4 kg CO_2e/year, which is the embodied carbon in the monitoring equipment that is necessary for deriving the inputs to the tool.

When compared to traditional approaches for addressing thermal increases on the network therefore, Passcomm CoolFlow DCM (plus the K^{e}LVN monitoring solution) and EkkoSense (plus the K^{e}LVN monitoring solution) deliver carbon savings of 3,863 kg CO_2e and 3,830 kg CO_2e respectively when used as part of the Celsius methodology. Where the Monitoring/Thermal Rating Tool is installed and identifies latent transformer capacity, it is estimated that this can provide a saving of 3,934 kg CO_2e relative to the traditional approach of replacing the transformer. These savings are summarised in the table below.

Celsius Technique	Carbon impact of Celsius (kg CO_2e)	Carbon impact of Traditional approach (kg CO_2e)	Carbon impact of Celsius relative to Traditional approach (kg CO_2e)
Passcomm CoolFlow DCM *(+ monitoring)*	75	3,938	-3,863
EkkoSense *(+ monitoring)*	108	3,938	-3,830
Monitoring/Thermal Rating Tool	4	3,938	-3,934

Extrapolation of Celsius' carbon savings to Electricity North West's DNO area

To enable calculation of Celsius' carbon impact at the DNO level, it was assumed that Passcomm CoolFlow DCM, EkkoSense and the Monitoring/Thermal rating Tool would each defer replacement of 33% of the total number of overloaded transformers (per year) in ENW's DNO area.

The analyses showed that if deployed across Electricity North West's (ENW's) DNO area, Celsius has the potential to save 348, 802 kg CO_2e per year relative to traditional methods for addressing transformer overloading. This is summarised in the table below.

Celsius Technique	Comparative carbon impact per application (kg CO_2e)	*Assumed* No. of transformer replacements deferred per year	Net carbon impact across DNO area (kg CO_2e /year)
Passcomm CoolFlow DCM *(+ monitoring)*	-3,863	30	-115,890
EkkoSense *(+ monitoring)*	-3,830	30	-114,890
Monitoring/Thermal Rating Tool	-3,934	30	-118,022
Total potential carbon impact per year of Celsius across ENW's DNO area, *relative* to traditional approaches for managing increasing thermal levels			**-348,802**

Extrapolating these annual carbon savings to 2050, suggests that implementation of Celsius techniques could result in carbon savings of 10,464,053 kg CO_2e over that period in ENW's area.

Extrapolation of Celsius' carbon savings to the GB electricity distribution network

Assuming a similar split for the application of Celsius techniques to overloaded transformers and scaling proportionally to the number of ground mounted secondary transformers in GB, the analyses estimate that Celsius' Passcomm CoolFlow DCM, EkkoSense, and Monitoring/Thermal

Rating Tool have the potential to save 4,513,905 kg CO_2e per year, if deployed across Great Britain's electricity network.

This is summarised in the Table below.

Celsius Technique	Comparative carbon impact per application (kg CO_2e)	*Assumed* No. of transformer replacements deferred per year	Net carbon impact across GB (kg CO_2e /year)
Passcomm CoolFlow DCM *(+ monitoring)*	-3,863	388	-1,499,750
EkkoSense *(+ monitoring)*	-3,830	388	-1,486,815
Monitoring/Thermal Rating Tool	-3,934	388	-1,527,340
Total potential carbon impact of Celsius per year across GB, *relative* to traditional approaches for managing increasing thermal levels			**-4,513,905**

Extrapolating these annual carbon savings to 2050, suggests that implementation of Celsius techniques could result in carbon savings of 135,417,161 kg CO_2e over that period, across GB's electricity distribution network.

Summary

The carbon impact assessment shows that relative to traditional approaches, the Celsius techniques assessed, namely the *Thermal Rating Tool* and the active *Retrofit Cooling technologies*, i.e., Passcomm CoolFlow DCM and EkkoSense, provide opportunities for reducing the carbon emissions associated with management of increasing thermal levels arising from increasing loads at electricity distribution substations.

Table of Contents

Abbreviations and Glossary

Acronym	Definition
BAU	Business As Usual
CO_2e	Carbon Dioxide equivalent
DNO	Distribution Network Operator
ENW	Electricity North West
GB	Great Britain
GhG	Greenhouse Gas
kg	Kilogrammes
kWh	Kilowatt Hour
LCA	Life Cycle Assessment
LCI	Life Cycle Inventory
LCT	Low Carbon Technologies

1 Introduction

1.1 Purpose of this report

Since 2016, Electricity North West (ENW) has been undertaking the innovative Celsius project, funded via Ofgem's Network Innovation Competition (NIC) mechanism.

FuturoFirma Sustainability Consulting have been commissioned by ENW to undertake an assessment of the Carbon impact of Celsius *vis-à-vis* traditional approaches for managing thermal increases at electricity distribution substations. *(In this context 'Carbon' is an umbrella term for the suite of gases that contribute to the greenhouse effect, and should be interpreted as such throughout this report.)*

This document summarises the outcomes and conclusions of that Carbon Impact Assessment.

1.2 The Celsius Project

ENW's Celsius project is exploring innovative, cost-effective approaches for managing potentially excessive temperatures at distribution substations, which could otherwise constrain the connection of low carbon technologies (LCTs).

Specifically, Celsius has developed methodologies for better understanding the real thermal ratings of distribution substation assets and has identified retrofit cooling interventions that can mitigate thermal impacts arising from increasing demand, thus unlocking capacity.

The three Celsius methodologies are described in Figure 1 below:

Retrofit Thermal Monitoring	• Improved technology have been utilised to measure asset and ambient temperatures, and relate these to a range of environmental, load and seasonal factors; in order to enable better understanding of real thermal ratings of assets. This will establish the availablity of latent capacity that could be accessed without further intervention.
Thermal Ratings Tool	• A simple tool has been developed - using the learning from the retrofit thermal monitoring trials and associated analysis. The tool can be used by operations and planning employees at any network operator, to better understand the capacity of the existing or planned network.
Retrofit Cooling	• A range of retrofit cooling technologies have been identified, that can be used to directly manage the temperature of assets. By managing temperature in this way, Celsius will deliver additional capacity release.

Figure 1: Celsius methodologies for thermal management at electricity substations

1.3 The potential for Celsius to have carbon impacts

To ensure that networks operate safely, electricity assets have a manufacturer assigned capacity rating, expressed in kVA, to indicate the maximum amount of energy they can carry.

If demand for electricity at a substation exceeds this static rating, the traditional approach is to replace affected assets - primarily the transformer, with new higher-capacity equipment. This is asset intensive and requires capital works, and therefore has significant carbon impacts.

The fundamental hypothesis underpinning the Celsius project is that implementation of the Celsius techniques can extend the useful life of key network assets and defer capital-intensive asset replacement.

Specifically, by enabling better understanding of the thermal behaviour of network assets under operation, establishing latent capacity that can be released quickly with no intervention and utilising a range of effective retrofit cooling techniques, Celsius has the potential to delay the replacement of assets when demand increases.

In this regard, Celsius presents potential for carbon savings relative to the traditional approaches for managing thermal increases at substations.

It should be noted however, that Celsius will also have some carbon impacts/penalties associated with some of its techniques, particularly those techniques that involve the installation of equipment.

In estimating the net carbon impact of Celsius *vis-à-vis* traditional approaches therefore, Celsius' gross carbon impact must be determined and compared to the carbon impacts of traditional approaches for managing thermal increases at electricity distribution substations.

1.4 Structure of this report

The remainder report is set out as follows.

Section 2: Sets out the methodology for undertaking the Celsius carbon impact assessment

Section 3: Provides a comparative assessment of the carbon impact of the Celsius' equipment relative to traditional approaches for responding to thermal increases at electricity distribution substations

Section 4: Provides conclusions and a summary of the analyses and findings

2 Methodology

2.1 Goal definition and scope

By deferring traditional asset replacement when increasing demand drives up temperatures at substations, and avoiding the embodied carbon associated with those assets and works, Celsius – when rolled out as BAU, has the potential to realise carbon savings relative to such traditional approaches.

The goal of this analysis therefore, is to assess the life-cycle carbon impact of BAU Celsius techniques relative to traditional approaches for thermal management at electricity distribution substations.

In the first instance, the assessment is undertaken at the substation level. To show the potential carbon impacts of Celsius at wider scale however, extrapolation techniques are subsequently applied to derive an estimate of Celsius' carbon impacts at both the DNO and GB distribution network levels.

2.2 Celsius techniques and components in scope

As previously described, the Celsius project have developed three categories of techniques and interventions for understanding and mitigating thermal increases at substations. Each Celsius technique category in turn have one or more components.

Table 1 below shows all the components of the three Celsius techniques and identifies those components that are in scope for this assessment.

Table 1: Celsius techniques in scope for this assessment

Celsius technique	Components of the technique	In Scope for this assessment?
Retrofit Thermal Monitoring	Single Temperature Sensors	In Scope
	Hex Sensor units	In Scope
	The Hub	In Scope
Monitoring for application of the Thermal Ratings Tool	Single Temperature Sensors	In Scope
	Hex Sensor units	In Scope
	The Hub	In Scope
Retrofit Cooling	Passcomm CoolFlow DCM	In Scope
	EkkoSense	In Scope
	Improving ventilation	*Out of Scope*
	Painting outdoor transformers	*Out of Scope*
	Shading outdoor transformers	*Out of Scope*
	Improved Cable Backfill	*Out of Scope*

It will be noted that there are four (4) retrofit cooling sub-techniques that have been deemed as out of scope for this assessment, namely *improving ventilation, painting outdoor transformers, shading outdoor transformers and cable backfills*. All four excluded sub-techniques are *passive* retrofit cooling approaches.

It was decided to exclude these from the analyses as their carbon impact is deemed to be minimal.

Indeed, three of these techniques, i.e., *improving ventilation, painting outdoor transformers, shading outdoor transformers* were assessed during the Celsius trials. However, whilst they are assumed to provide benefits in terms of reducing temperature at substations, statistically significant data to prove their impact on transformer ratings were not available or/and consistent during the trials. As such, their ability to defer transformer replacement was not explicitly proven.

The fourth passive cooling technique, *Improved Cable backfill*, was not assessed during the Celsius trial, and therefore no definitive determination can be made about its impact of transformer ratings and/or deferring transformer replacement.

Therefore, of the Celsius retrofit cooling techniques, only the *active* technologies, i.e., Passcomm CoolFlow DCM and EkkoSense, are in scope for this carbon assessment.

In particular, data from the Celsius trials show that at a minimum, Passcomm and EkkoSense can respectively provide a 14% and 12% improvement in transformer ratings.

2.3 Emission Sources for this assessment

Having established the Celsius techniques and sub-techniques that are in scope for this assessment in section 2.2 above, Table 2 below comprehensively shows the sources of life-cycle emissions that are considered in this comparative assessment of Celsius relative to traditional responses to thermal increases at electricity substations.

Table 2: Life-cycle emission sources in this assessment

Emission sources for BAU approach for responding to increased thermal levels at substations	
Transformer replacement	When thermal rating at substations are expected to be exceeded due to increase in demand, the traditional response is to replace the transformer
Emission sources for Celsius approaches for managing thermal levels at substations	
Celsius K^{e}LVN monitoring solution	
Single Temperature Sensors	*These measure the temperature at a specific point. This can either be ambient conditions or the surface temperature of assets.*
Hex Sensor units	*Hex sensor units can be used to monitor 6 independent inputs using flying leads to measure Temperature, Voltage and Current.*
The Hub	*The hub acts as low power radio concentrator and has cellular modem. This unit collects the data from the sensors onsite and sends the data to the monitoring data management system.*
***Active* Celsius retrofit Cooling technologies**	
Positive pressure active cooling – *Passcomm CoolFlow DCM*	*This system works by creating a positive pressure inside the substation. External air is blown into the substation and forced out of high-level vents.*
Negative pressure active cooling – *EkkoSense*	*This system works by drawing hot air away from the transformer and expelling it through a duct outside of the substation.*
Celsius Thermal Rating Tool (including the underpinning monitoring)	
Thermal rating Tool	*The Thermal Rating tool predicts more informed transformer ratings. Accordingly, it can identity spare/latent transformer capacity, thus deferring the need to replace the transformer when demand increases. (Notably, inputs for the Thermal rating Tool are derived using the Celsius K^{e}LVN monitoring solution.)*

2.4 ISO 14044 as a basis for the assessment

To ensure that all relevant carbon is considered for the in-scope Celsius techniques, a Life Cycle Assessment (LCA) approach – in accordance with ISO 14044, is applied for undertaking the carbon assessment.

ISO 14044 specifies requirements and provides guidelines for undertaking a life cycle assessment (LCA). The key stages include: definition of the goal and scope of the LCA, the life cycle inventory analysis (LCI) phase, the life cycle impact assessment (LCIA) phase, the life cycle interpretation phase, reporting and critical review of the LCA, limitations of the LCA, relationship between the LCA phases, and conditions for use of value choices and optional elements.

As with previous carbon assessments for ENW innovation projects however, the *Disposal* phase of the product life cycle is excluded (See for example Jones 2018). The *Disposal* phase is often excluded in LCA where it is assumed that this phase has minimal impact (Fthenakis *et al*, 2011).

All other stages of the life cycle are considered.

2.5 Embodied emissions in network assets

As a significant proportion of the carbon impacts from the traditional and Celsius' approaches for managing increasing thermal levels, will emanate from the network assets, the concept of 'embodied' emissions is highly relevant.

In simplest terms, embodied emissions refer to the carbon emitted to extract, refine, process, transport and fabricate a material or product.

To calculate embodied carbon, it is often necessary to collate a Life Cycle Inventory (LCI) – which quantifies the material and energy flows of the asset.

As part of this assessment, the LCI for some assets, specifically the equipment for the Celsius monitoring and retrofit cooling techniques, had to be developed from scratch (as no previous LCI had been developed for them).

In the case of the LCI for electricity distribution transformers, it was possible to draw on previous work, including outputs from past ENW innovation projects - specifically the *Smart Street* project, as well as the academic literature.

Table 3 below shows the data sources for the LCIs used or developed in this assessment

Table 3: Data sources for the LCIs used in undertaking the carbon assessment

Carbon data required	Data Source
Embodied carbon of Transformer / Transformer replacement	Jones, C., *Deliverable 3.4.3 "Report on the Carbon Impact Implications of the Smart Street Method at ENWL and Great Britain Scale"*. 2018 Turconi et al, *Life cycle assessment of the Danish electricity distribution network,* International Journal of Life Cycle Assessment 19 (2014) 100-108
Embodied carbon in the applicable Celsius BAU equipment, i.e., The K^{e}LVN monitoring solution, EkkoSense and the Passcomm CoolFlow DCM	Manufacturing data obtained from the respective manufacturers, namely Ash Wireless , EkkoSense and Passcomm
Embedded carbon in the Celsius Thermal Rating Tool	Whilst the Thermal Rating Tool, which is an MS Excel Workbook has no embedded carbon; monitoring (using the KeLVN monitoring solution) has to be undertaken in order to derive the inputs for the tool. Accordingly, data for the KeLVN monitoring solution (above) are also applicable for the Thermal Rating Tool.

2.6 Calculating the net carbon impact of the Celsius approach

In simplest terms, the net carbon impact of Celsius is the difference between the the carbon impact of Celsius and the carbon impact of the traditional approach for managing/responding to increasing thermals levels on the network.

This is summarised in the following equation:

$$CI = \sum_{y=0}^{n} TA_{CI} - S_{CI}$$

Where:

CI is the comparative carbon impact of Celsius relative to traditional approaches

TA_{CI} is the carbon emissions from Traditional approach for addressing thermal increases at electricity substations, i.e., by replacing the transformer

S_{CI} is the carbon emissions from the Celsius approach for addressing thermal increases at electricity substations

3 Results

This section presents the results of the analyses. The net carbon impacts of the Celsius techniques in consideration, i.e., the *Thermal Rating Tool* (including the monitoring that underpins it) and the active *Retrofit Cooling technologies*, i.e., Passcomm CoolFlow DCM and EkkoSense, are calculated and compared to the carbon impacts of traditional approaches for managing thermal levels/increases on the network, i.e., replacing the transformer.

3.1 Carbon impact of the EkkoSense cooling solution

A bottom-up approach was employed as part of this project to collate the required data in order to develop the LCI and calculate the embodied carbon in the EkkoSense cooling equipment.

To enable this, the manufacturers (EkkoSense) were contacted, who provided an estimate of the materials used in its manufacture. Greenhouse Gas (GHG) emission factors were then applied to calculate embodied carbon from the material mass.

Table 4 shows the carbon embodied in the materials used in the manufacture of EkkoSense.

Table 4: Embodied carbon in EkkoSense

Material	Amount (kg)	Emission Factors	kg CO_2e
Steel	1.55	2.30E+00	3.6
Copper	0.1	3.30E+00	0.3
PVC	10.56	1.86E+00	19.6
Polyester	5.5	1.22E+01	67.1
ABS	7.39	1.86E+00	13.7
Sub Total	**25.10**		**104.4**

3.2 Carbon Impact of Passcomm CoolFlow DCM

A bottom-up approach was also employed to collate the required data to develop an LCI and calculate the embodied carbon in the Passcomm CoolFlow DCM.

Details of the materials used in the manufacture of CoolFlow DCM were sourced and obtained from the manufacturer Passcomm. Based on the information provided, an LCI was derived as below, which estimates the embodied carbon in the Passcomm CoolFlow DCM at **71 kg CO_2e** per unit.

Table 5: Embodied carbon in the Passcomm CoolFlow DCM

Material	Amount (kg)	Emission Factors	kg CO_2e
Aluminium	0.37	8.20E+00	3
Steel	20.30	2.30E+00	47
Copper	0.30	3.30E+00	1
Grass - CF3 filter media	2.80	1.86E+00	5
Ultramid A3U40G5	2.03	6.00E+00	12
Volatex 4012	0.01	8.07E+00	0
Latamid 66H2 G/25-VOHF-1	0.70	2.42E+00	2
BETAtrans 3GKW flex	0.36	3.30E+00	1
Total	**28.67**		**71**

3.3 Carbon Impact of the Celsius monitoring equipment

One of the benefits of Celsius arises from the enhanced thermal monitoring that it provides at distribution substations. The details of the Celsius K[e]LVN monitoring solution is described in *BAU Monitoring Solution Specification for the Celsius project* (Ricardo Energy and Environment 2019a). A brief summary is provided below.

The main components of the monitoring solution are:

- **Single Temperature Sensors**: These measure the temperature at a specific point, which can either be ambient conditions or the surface temperature of particular assets. The temperature sensor is specified to within 0.1°C resolution.

- **Hex Sensor units**: These can be used to monitor 6 independent inputs using flying leads to measure Temperature, Voltage and Current. Hex Sensor units can also be configured for Power Measurement and use paired Voltage and Current Flying Leads to measured power on 3 phases. Voltage and current are measured every 30 seconds, and the average of these readings over 30 minutes is recorded as the reading.

- **The Hub**: The Hub acts as low power radio concentrator and has a cellular modem. This unit collects the data from the sensors onsite. Once per day it sends the data to the monitoring data management system.

As with the other Celsius equipment, the LCI for the monitoring equipment had to be developed from scratch using data provided by manufacturer, Ash Wireless.

These LCIs are shown in the tables below.

Table 6: Embodied carbon in the Hex Sensor or Hub

Material	Amount (kg)	Emission Factor	Kg CO_2e
Steel	0.04	2.30E+00	0.1
Copper	0.01	3.30E+00	0.0
Brass	0.00	3.30E+00	0.0
FR4	0.03	8.07E+00	0.2
Glass-filled PC/ABS	0.40	1.86E+00	0.7
Neodymium	0.02	1.76E+01	0.3
Total	**0.49**		**1.4**

Table 7: Embodied carbon in the Temperature Unit

Material	Amount (kg)	Emission Factor	Kg CO_2e
Steel	0.01	2.30E+00	0.01
Copper	0.00	3.30E+00	0.00
FR4	0.01	8.07E+00	0.05
Glass-filled PC/ABS	0.09	1.86E+00	0.16
Neodymium	0.01	1.76E+01	0.18
	0.11		**0.40**

3.4 Carbon Impact of Celsius Monitoring in the application of the Celsius Thermal Rating Tool

As previously mentioned, most transformers have more capacity than their nominal ratings suggest for most of the time. The Thermal Rating tool, which is in the form of an MS Excel Workbook, predicts more informed ratings for Low Voltage transformers. Accordingly, it can identity spare/latent transformer capacity, thus deferring the need to replace the transformer when the nominal capacity rating is deemed at risk of being exceeded.

Monitoring, using Celsius Celsius K^{e}LVN monitoring solution, needs to be undertaken in order to provide site-specific inputs into the Thermal rating Tool.

Accordingly, the carbon impact of the Celsius Thermal Monitoring Tool arises from the embodied carbon in the K^{e}LVN monitoring equipment, namely the Hub, Hex Sensor Units and Temperature Sensor Units. As shown in Table 8 below, this is estimated **4 kg CO_2e** per installation.

Table 8: Embodied carbon in the Celsius Monitoring/ Thermal Rating Tool

Monitoring equipment	Emissions per unit Kg CO_2e	Quantity at a substation	Total emissions Kg CO_2e
Monitoring-Hub	1.4	1	1.4
Hex Sensor Unit	1.4	1	1.4
Monitoring - Temp Unit	0.4	3	1.2
Total emissions associated with Celsius Monitoring/Thermal Rating Tool			**4**

3.5 Carbon impacts of the *traditional* approach for thermal management at distribution substations

As previously mentioned, when demand for electricity at a substation is deemed at risk of exceeding its capacity rating, the traditional approach for addressing this is to replace affected assets, primarily the transformer, with new higher-capacity equipment.

For the purpose of this assessment therefore, the carbon impact of the traditional approach for addressing thermal increases at substations, is deemed to be the embodied carbon in the transformer.

Previous ENW Innovation projects, specifically the *Smart Street* project, have undertaken an assessment of the embodied carbon in transformers in ENW's licence area (see Jones 2018 for more detail of the Smart Street carbon assessment). This was based on some contextualisation of work that had previously been done by Turconi *et al* (2014), who had provided LCI data for transformers in the Danish context.

To ensure consistency with previous ENW projects, it was decided that this assessment would utilise the LCI and carbon emissions reported by the *Smart Street* project for an ABB 10/0.4 KV (335 kVA) transformer.

Notably, the assessment undertaken as part of the Smart Street project found the life cycle GhG emissions for an ABB 10/0.4 KV 335kVA transformer to be **3,938 kgCO_2e.**

Figure 2 below shows the basis for the derivation of that number, in terms of the materials and their proportions used by Jones *et al* (2018) in their assessment of embodied carbon in transformers for the Smart Street project.

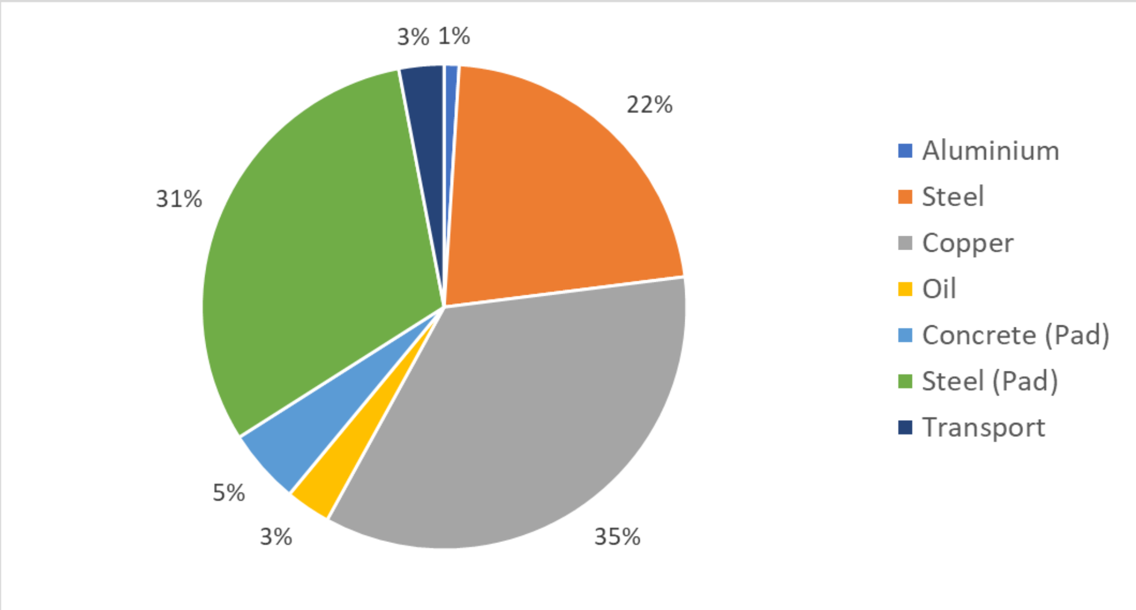

Figure 2: Materials and their proportions used in assessing carbon impact of transformers

To ensure consistency with previous ENW innovation projects, the embodied emissions calculated for a transformer used in the Smart Street projects, are also used in this assessment, i.e., **3,938 kgCO_2e** in a transformer.

3.6 Comparative carbon impact of Celsius techniques relative to traditional approaches for managing thermal levels

The net carbon impact of utilising Celsius for managing/addressing thermal increases at a distribution substation, relative to traditional approaches, is calculated by subtracting the carbon impact of the respective Celsius technique from the carbon impact of the traditional approach, i.e. replacing the transformer.

Notably, it is not intended that the two active retrofit cooling technologies, i.e., Passcomm CoolFlow DCM and EkkoSense, will be used simultaneously at a single substation. Only one – or the other, will be used at any given time.

Accordingly therefore, in undertaking a comparative analyses to traditional approaches, separate assessments have to be undertaken for Passcomm CoolFlow DCM and EkkoSense.

It is expected that the monitoring solution will be part of any implementation of the Celsius methodology, irrespective of whether PassComm CoolFlow DCM or EkkoSense is utilised. Consequently therefore, the embodied carbon in the monitoring equipment are considered under both scenarios.

It should be noted that several temperature sensors will typically be used at a single substation – as part of the Celsius monitoring approach. The number per installation varies. However, for the purpose of this analysis, it is assumed that three (3) temperature sensors are utilised per Celsius monitoring implementation.

3.6.1 Carbon impact of Passcomm relative to the traditional approach

Using the assumptions articulated above, Table 9 below shows the comparative impact of Celsius – when using Passcomm CoolFlow DCM for active retrofit cooling, relative to the traditional approach of replacing the transformer.

Table 9: Carbon impact of Celsius relative to Traditional approach (when using Passcomm)

Celsius approach for thermal management	Quantity at a substation	Emissions per unit	Total
Passcomm	1	71	71
Monitoring-Hub	1	1	1
Monitoring Hex Sensor Unit	1	1	1
Monitoring - Temp Unit	3	0.4	1
Total Celsius emissions			*74*
Traditional approach for thermal management			
Replacing transformer at substation	1	3938	3938
Total emissions from traditional approach			*3938*
Celsius carbon impact relative to traditional approach for thermal management (when using the Passcomm CoolFlow DCM for retrofit cooling)			**-3863**

As shown above, where Passcomm CoolFlow DCM active retrofit cooling, is deployed for managing thermal increases at substations - as opposed to replacing the transformer, it is estimated that up to **3,863 kg CO_2e** can be saved per affected substation.

3.6.2 Carbon impact of EkkoSense relative to the traditional approach

Table 10 below shows carbon impact of Celsius relative to traditional approaches, when EkkoSense is utilised for active retrofit cooling.

Table 10: Carbon impact of Celsius relative to Traditional approach (when using Ekkosense)

Celsius approach for thermal management	Quantity at a substation	Emissions per unit	Total
EkkoSense	1	104	104
Monitoring-Hub	1	1	1
Monitoring Hex Sensor Unit	1	1	1
Monitoring - Temp Unit	3	0.4	1
Total Celsius emissions			*108*
Traditional approach for thermal management			
Replacing transformer at substation	1	3938	3938
Total emissions from traditional approach			*3938*
Celsius carbon impact relative to traditional approach for thermal management (when using EkkoSense for retrofit cooling)			**-3830**

As shown above, where EkkoSense retrofit cooling, is deployed for managing thermal increases at substations - as opposed to replacing the transformer, it is estimated that up to **3,830 kg CO_2e** can be saved per affected substation.

3.6.3 Carbon impact arising from application of Monitoring/Thermal Rating Tool relative to the traditional approach

As outlined in section 3.4, the carbon arising from applying the Thermal rating Tool is due to the monitoring that has to be undertaken to derive the inputs for the tool.

As shown in Table 11 below, where Celsius monitoring and the Thermal Rating Tool is applied, and where that application results in the identification of further capacity (above and beyond the nominal rating of the transformer), it is estimated that up to **3,934 kg CO_2e** can be saved per affected substation relative to the traditional approach of replacing the transformer.

Table 11: Carbon impact of the Celsius Thermal Rating Tool relative to the traditional approach

Monitoring equipment to provide inputs for Thermal Rating Tool	Quantity at a substation	Emissions per unit	Total
Monitoring-Hub	1	1	1
Monitoring Hex Sensor Unit	1	1	1
Monitoring - Temp Unit	3	0.4	1
Total Celsius emissions			*4*
Traditional approach for thermal management			
Replacing transformer at substation	1	3938	3938
Total emissions from traditional approach			*3938*
Celsius carbon impact relative to traditional approach for thermal management (when using EkkoSense for retrofit cooling)			**-3934**

3.7 Extrapolation of Celsius' carbon savings to ENW's DNO area

ENW, like all Network Operators, have traditionally replaced transformers when they exceed or deemed to be at risk of exceeding their thermal ratings.

Analyses undertaken by Ricardo Energy & Environment Ltd. (2019), based on the Future Capacity Headroom (FCH) and load growth assumptions, estimates that 2,710 transformers in ENW's area could be overloaded by 2050. (This translates to circa 90 transformers per year.)

In this section of the report, it is assumed that Celsius techniques would be implemented at all of the overloaded transformers in ENW's area, as opposed to the traditional intervention of replacing the transformer. This and other related assumptions are set out in Table 12 below.

Table 12: Assumptions made in extrapolating Celsius' carbon savings to ENW's DNO area

Transformer overloading	It is assumed that ninety (90) transformers per year become overloaded in ENW's DNO area. It is further assumed that Celsius techniques are implemented at all of the overloaded sites.
Passcomm installations	It is assumed that Passcomm CoolFlow DCM would be installed at 33% of the overloaded sites, i.e., 30 transformers per year
EkkoSense installations	It is assumed that EkkoSense would be installed at 33% of the overloaded sites, i.e., 30 transformers per year
Additional capacity identified due to utilisation of Monitoring/Celsius Thermal Rating Tool	It is assumed that sufficient latent capacity would be identified at 33% of the overloaded sites, i.e., 30 sites per year, to defer replacement of those transformers at those sites

3.7.1 Estimated carbon savings from deploying Celsius across ENW's DNO area

Applying the assumptions shown above, and comparing the carbon impact of the Celsius techniques to the carbon impact of traditional approaches for addressing increases in transformer thermal levels, shows that Celsius has the potential to save **348,802 kg CO_2e per year** across ENW's DNO area (see Table 13 for details).

Table 13: Potential Celsius carbon savings across ENW's DNO area per year

Celsius Technique	Comparative carbon impact per installation kg CO_2e	*Assumed* No. of transformer replacements deferred per year	Total Comparative carbon impact (kg CO_2e per year)
Passcom	-3,863	30	-115,890
EkkoSense	-3,830	30	-114,890
Monitoring/Thermal Rating Tool	-3,934	30	-118,022
Total potential carbon impact per year across DNO area *relative* to traditional approaches for managing increasing thermal levels			**-348,802**

Extrapolating these annual carbon savings to 2050, suggests that implementation of Celsius techniques could result in carbon savings of 10,464,053 kg CO_2e over that period in ENW's area.

3.8 Extrapolation to the GB electricity distribution system

In order to estimate Celsius potential roll out across over GB, *Ricardo Energy & Environment* (2019) proportionately multiplied the number of ENW overloaded sites to the number of ground mounted distribution transformers in GB.

As it is estimated that there are 220,000 ground mounted secondary transformers in GB, of which 17,000 are in the Electricity North West area, a scaling factor of 12.94 for Celsius was derived.

Applying this scaling factor to the projected numbers of overloaded transformers in ENW's DNO area shown in section 3.7 above, results in an estimate of 1165 overloaded transformers per year across GB.

It is assumed that the proportion of transformer replacements that could be deferred due to utilisation of Passcomm, EkkoSense and the Thermal rating Tool in each licence area would be similar to those applied above for extrapolating the results to ENW's DNO area, i.e., 33% for each Celsius method.

Based on these assumptions, Table 14 below shows that Celsius has the potential to save **4,513,905 kg CO_2e** per year, if deployed across Great Britain.

Table 14: Potential Celsius carbon savings across Great Britain

Celsius Technique	Comparative carbon impact per installation kg CO_2e	*Assumed* No. of transformer replacements deferred per year	Total Comparative carbon impact (kg CO_2e per year)
Passcom	-3,863	388	-1,499,750
EkkoSense	-3,830	388	-1,486,815
Monitoring/Thermal Rating Tool	-3,934	388	-1,527,340
Total potential carbon impact per year across GB *relative* to traditional approaches for managing increasing thermal levels			**-4,513,905**

Extrapolating these annual carbon savings to 2050, suggests that implementation of Celsius techniques could result in carbon savings of 135,417,161 kg CO_2e over that period, across GB's electricity distribution network.

4 Conclusions and summary

The LCA of Celsius' carbon impact shows that relative to traditional approaches, the *Monitoring/Thermal Rating Tool* and the active *Retrofit Cooling technologies*, i.e., Passcomm CoolFlow DCM and EkkoSense, provide opportunities for significantly reducing the life-cycle carbon emissions associated with addressing demand-related thermal increases at distribution substations.

Indeed, each installation of the Passcomm or EkkoSense retrofit cooling solution (plus the Celsius' K^eLVN monitoring solution), has the potential to reduce carbon emissions by 3,863 kg CO_2e and 3,830 kg CO_2e respectively *vis-à-vis* traditional interventions. Where the *Thermal Rating Tool* and the monitoring that underpins it, identifies additional transformer capacity, this could realise savings of 3,934 kg CO_2e relative to traditional approaches.

If rolled out across ENW's DNO area, Celsius has the potential to save 348,802 kg CO_2e per year; and if rolled out across GB, 4,513,905 kg CO_2e per year can be saved per year.

References

Jones, C (2018): *Deliverable 3.4.3 "Report on the Carbon Impact Implications of the Smart Street Method at ENWL and Great Britain Scale"*

Fthenakis V, Frischnecht R, Raugei M, Kim H. C., Alsema E, Held N, de Wild-Scholten M (2011): *Methodology Guidelines on Life Cycle Assessment of Photovoltaic Electricity*, 2nd edition, IEA PVPS Task 12, 2011.

Ricardo Energy & Environment (2019*a*): Celsius *BAU Monitoring Solution Specification*

Ricardo Energy & Environment (2019*b*): *Celsius Solutions: Cost Benefit Analysis and Buy Order*