TRACING THE CARBON INTENSITY OF ACTIVE POWER FLOWS IN DISTRIBUTION NETWORKS

Euan DAVIDSON
Smarter Grid Solutions – UK
edavidson@smartergridsolutions.com

Robert CURRIE
Smarter Grid Solutions – UK
rcurrie@smartergridsolutions.com

Young-Ho KWON
Smarter Grid Solutions – UK
ykwon@smartergridsolutions.com

Jorge PEÑA-MARTÍNEZ
Smarter Grid Solutions – UK
jmartinez@smartergridsolutions.com

Neil McNEILL
Smarter Grid Solutions – UK
nmcneill@smartergridsolutions.com

Roger HEY
Western Power Distribution - UK
rhey@westernpower.co.uk

ABSTRACT

This paper describes a method for tracing the carbon intensity of power flows in distribution networks. The method accounts for carbon emissions associated with local consumption of electrical energy and system losses. The motivation for the approach and its use as an instrument for public engagement is discussed. Methods for the visualisation of the results of carbon-tracing are presented.

INTRODUCTION

At the present time, there is little visibility of the carbon emissions associated with the electricity supplied at a local level in the UK. Whilst figures can be derived for the national energy picture in timescales commensurate with market closure, it is not clear what the associated carbon intensity (grams of CO_2 per kWh) of the energy being delivered via distribution networks is and therefore what the carbon intensity of electricity being consumed by customers might be. Similarly, losses are characterised in terms of energy and not the emissions associated with the loss of that energy at the local level.

Distribution Network Operators (DNOs) do not currently consider grams of CO_2 per kWh of energy delivered through their infrastructure as a parameter that can be identified, quantified and addressed through some kind of mitigating action, partnership or investment. Similarly, customers may have little understanding of: where there electricity comes from at a local level; and how their acceptance of local renewable energy sources and their patterns of use affect the carbon content or carbon intensity they consume.

In this paper we explore the use carbon-tracing as a method for illustrating the local variations in the carbon intensity of electricity consumed by customers and the carbon intensity of flows and losses. The underlying method for carbon-tracing is based on an extension of the power-flow-tracing and loss-allocation techniques described in [1] [2] [3]. The carbon intensity of flows and losses are then calculated using the DEFRA emission factors [4] for types of generation plant and assigned to flows, losses and loads.

A number of approaches to visualisation of the different results provided by the carbon-tracing method have been explored. The paper presents a set of examples that illustrate the type of results carbon-tracing can yield. Finally, the possibility of using carbon-tracing as a tool for public engagement is discussed.

POWER FLOW TRACING

Power-flow-tracing emerged in the mid-1990s in response to the drive for deregulation and unbundling of electricity supply industries and resulting requirement for charging and loss allocation methodologies [1][2][3]. Power-flow-tracing techniques describe the power flows as directed graphs and then, based on that graph, apportion part of the flow to particular generators or loads. Within this paper, only active power flows are considered.

At the heart of the technique is the principle of proportional sharing (illustrated in Figure 1) where power flowing into a node is proportionally shared between the outgoing connections.

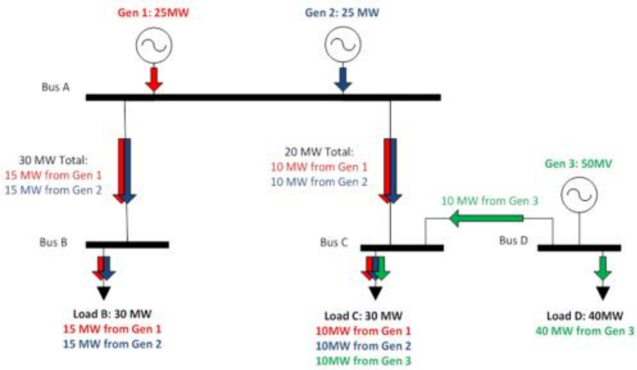

Figure 1: The proportional sharing principle

Methods for implementing power-flow-tracing can be categorized as numerical or graphical in nature. Numerical methods, e.g. [1] [2] [3], use linear algebra to calculate the apportionment of flows and losses to loads and generators based on an incidence matrix derived from a graph. Graphical methods, typified by [5] [6] [7] [8] [9] [10] [11], trace the flow from a generator to a load allocating the correspondent proportion of the active power flow to the generator.

Based on the results in [3], the numerical method described in [1] [2] was chosen as the foundation of a new method for allocating a proportion of emissions from generators to load, flows and losses.

The method in [1] [2] requires:

$\boldsymbol{P}$	- a vector of nodal flows;
$\boldsymbol{F}_{net}, \boldsymbol{F}_{gross}$	- vectors of branch flows;
$\boldsymbol{P}_G$	- vector of injections from generation
$\boldsymbol{P}_L$	- vector of loads

The structure and direction of the active power flows can be used to build a directed graph, described by the incidence matrix $\boldsymbol{B}$. In $\boldsymbol{B}$, the end and the beginning of a line are denoted by -1 and 1 respectively. $\boldsymbol{B}$ can be divided into a positive matrix $\boldsymbol{B}_d$ and a negative matrix $\boldsymbol{B}_u$.

A proportion of nodal flows can be equated to load or generation:

$$\boldsymbol{A}_d \boldsymbol{P} = \boldsymbol{P}_L$$
$$\boldsymbol{A}_u \boldsymbol{P} = \boldsymbol{P}_G$$

[3] describes how $\boldsymbol{A}_d$ and $\boldsymbol{A}_u$ can be derived:

$$\boldsymbol{A}_d = \boldsymbol{I} + \boldsymbol{B}_u{}^T\,(\mathrm{diag}\,\boldsymbol{F})\boldsymbol{B}_d(\mathrm{diag}\,\boldsymbol{P})^{-1}$$
$$\boldsymbol{A}_u = \boldsymbol{I} + \boldsymbol{B}_d{}^T\,(\mathrm{diag}\,\boldsymbol{F})\boldsymbol{B}_u(\mathrm{diag}\,\boldsymbol{P})^{-1}$$

Inverting $\boldsymbol{A}_d$ and $\boldsymbol{A}_u$ gives a set of distribution factors in terms of load and generation:

$$\boldsymbol{P} = \boldsymbol{A}_d{}^{-1}\boldsymbol{P}_L$$
$$\boldsymbol{P} = \boldsymbol{A}_u{}^{-1}\boldsymbol{P}_G$$

[3] provides a rigorous mathematical proof of the invertibility of the distribution matrix. Furthermore, [3] describes how losses can be allocated on a proportional basis.

CARBON TRACING

Carbon-tracing involves assigning carbon content or carbon intensity to flows, loads and losses. The concept is illustrated in Figure 2, extending the example in Figure 1.

The allocation of power flow, loads and losses for each generator are multiplied by the emissions factor for that generator's type.

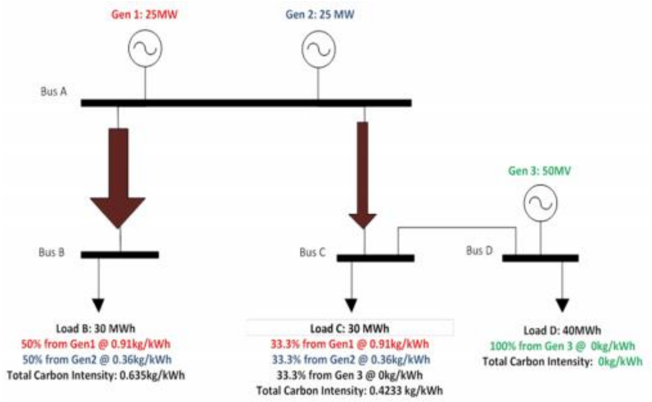

Figure 2: Allocating emissions to loads

The DEFRA emission factors [4] for the average emissions per kWh for different types of plant (if built new in 2012) used within the method can be found in **Error! Reference source not found.**.

Table 1: Emission Factors used for case studies

Type of generation	Carbon Intensity
Coal	0.32 kg/kWh
Oil	0.27 kg/kWh
Gas	0.18 kg/kWh
Biomass	0.25 kg/kWh
Nuclear	0.026 kg/kWh
Wind / Solar / Hydro	0.0 kg/kWh

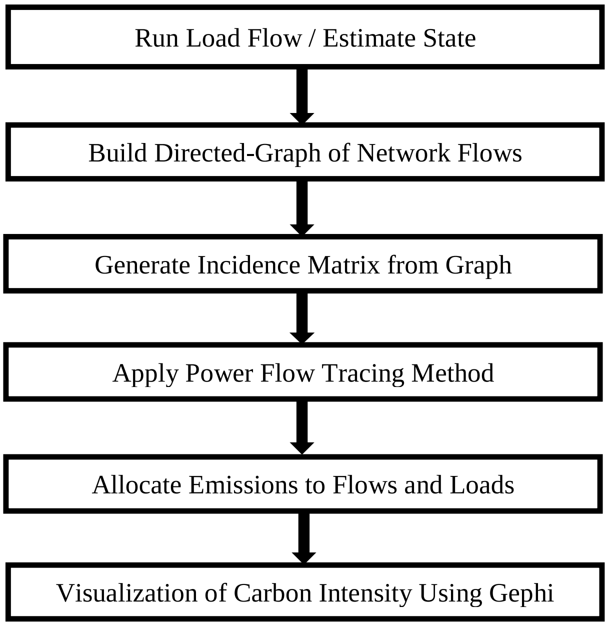

Figure 3: Carbon tracing algorithm

The process for carbon-tracing can be seen in **Error! Reference source not found.**. Based on the result of a full AC load flow or from state estimation, the method involves generating a directed graph that describes active flows. The incidence matrix required by the power-flow-tracing method above is generated from this directed graph.

Information derived by power-flow-tracing and the allocation of emissions is stored within the data structure of the directed graph and written to an xml file in the .gexf format [5].

An open source tool [6] has been used to visualise the graph and colour its edges based on the data stored within the graph description language. The following section illustrates this approach.

VISUALISING THE CARBON INTENSITY AND CARBON CONTENT OF FLOWS

Figure 4 shows carbon-tracing applied to the simple four bus example used in [1] and [2]. Flows are apportioned to generators using the technique above. The coal-fired power station is given an associated carbon intensity of 0.32 kg/kWh. Generator 2 is assumed to be a wind farm with a given carbon intensity of 0 kg/kWh. The carbon intensity of the flows is calculated based on the proportion of the flow assigned to each generator. The resulting graph is coloured to indicate the carbon-intensity of the flows.

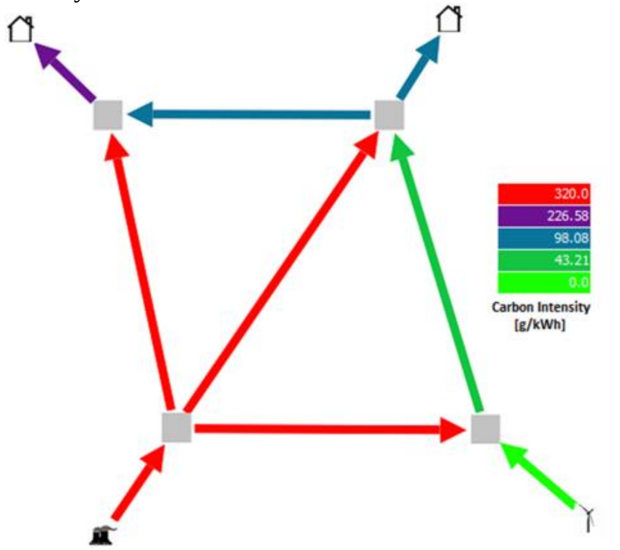

Figure 4: Carbon intensity [g/kWh] in four-bus system

Figure 5 shows the carbon content against time (kg/h) for each branch. The edges of the graph are coloured based on the calculated carbon content rather than the intensity of the flow. Illustrating carbon content gives a different view. However, the carbon content attributed to a flow on a given line may be low, and thus appear "orange", simply because the line loading is low.

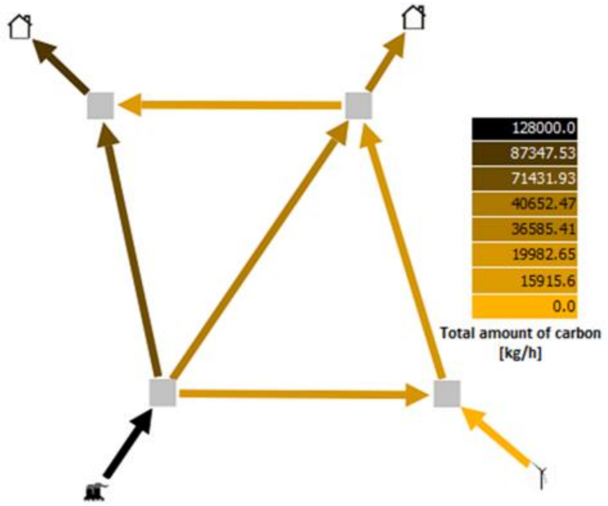

Figure 5: Total carbon volume per hour [kg/h]

Figure 6 shows a graph generated by a snapshot of data for a real 11 kV network in the UK. The grid import is assumed to have a carbon intensity of 0.49 kg/kWh, the average carbon intensity of the grid in-feed for the UK. This figure includes the carbon associated with losses and old power plants. Therefore, it is higher than any modern power source technology, such as the 0.32 kg/kWh for coal in Table 1. The network has three additional embedded generators: one small wind farm and two landfill generators. The colouring of the edges of the directed graph illustrates the local variation in the carbon intensity of flows and energy supplied in the areas close to the generators.

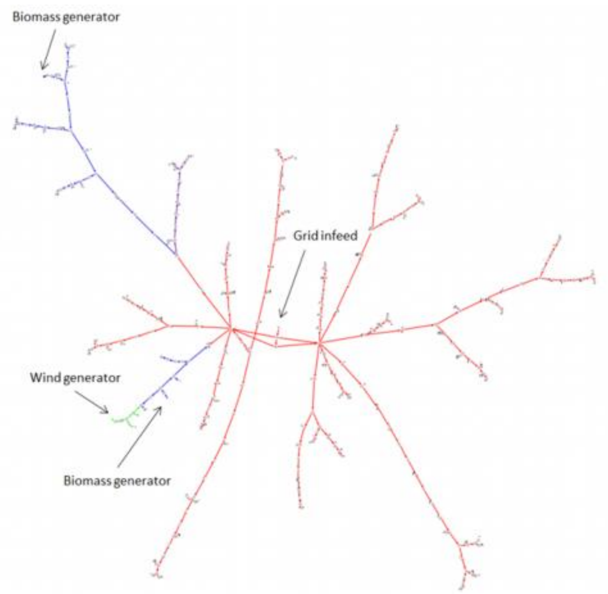

Figure 6: Carbon intensity [g/kWh] in an 11kV network

A TOOL FOR PUBLIC ENGAGEMENT ON LOCAL ENERGY SUPPLY ISSUES

Carbon-tracing techniques are primarily conceived as tools for public engagement and as a means of communicating to customers where their electricity comes from and how their usage affects the carbon emissions associated with the electricity they use. In the UK, the retail energy market separates consumers from the source of the energy they actually consume. Consumers' primary interactions are with supply/retail companies rather than the DNO.

Ecotricity, an energy supply company in the UK, publishes the macro-picture for the average carbon intensity of supply, estimated from market data, on its website [13].

In terms of visualising local carbon emissions, Arizona State University's Hestia project [14] aims to quantify CO_2 emissions on a local and temporal basis and display that information in a geographical manner. Emissions associated with generation are accounted for at source rather than at the point of use. However, the aims of Hestia, i.e. to provide a view to help planners, policy-makers and consumers understand and engage with CO_2 emissions, are in the same spirit as this endeavour.

Carbon-tracing gives a simple accounting method for estimating the carbon-intensity of electricity at the local level based on assumptions of the emission factors of different types of generator and the validity of the proportional sharing principle as an accounting method.

It is intended to explore other innovative ways of displaying information on the carbon intensity of load, flows and losses in ways that helps engage the public in conceptualising where their electrical energy comes from and how their energy use relates to emissions.

CONCLUSIONS

The power flow tracing methodology described in [1] [2] [3] can be extended to allocate carbon emission to loads and losses on distribution networks. As a method, it gives a view on the local level how the operation and use of the network, the connected renewable resources, and nature of load, affect emissions on a local level. It is intended to use the output of this accounting approach as an instrument for public engagement concerning local energy issues.

REFERENCES

[1] J. Bialek, 1996, "Tracing the flow of electricity", *Generation, Transmission and Distribution, IEE Proceedings*, Vol. 143. No. 4. IET.

[2] J. Bialek, 1997, "Topological generation and load distribution factors for supplement charge allocation in transmission open access", *IEEE Trans. Power Syst.*, vol. 12. no. 3, 1185-1193.

[3] C. Achayuthakan, C.J. Dent, J. Bialek and W. Ongsakul, 2010, "Electricity tracing in systems with and without circulating flows: Physical insights and mathematical proofs", *IEEE Trans. Power Syst.*, vol. 25, no. 2, 1078-1087.

[4] DEFRA and DECC, 2012, "2012 Guidelines to Defra / DECC's GHG Conversion Factors for Company Reporting", *Carbon Management.* vol. 1, 45-56. http://www.defra.gov.uk

[5] D. Kirschen, R. Allan, and G. Strbac, 1997, "Contributions of individual generators to loads and Flows", *IEEE Trans. Power Syst.*, vol. 12, no. 1, 52-60.

[6] FF. Wu, YX. Ni and P. Wei, 2000, "Power transfer allocation for open access using graph theory-fundamentals and applications in systems without loopflow", *IEEE Trans. PowerSyst.*, vol. 15, no. 3, 923-929.

[7] XF. Wang, Y. Song and M. Irving, 2008, *Modern Power system analysis*, Springer, 193-254.

[8] P. Wei, Y. NI and FF. Wu, 2002, "Load flow tracing in power systems with circulating power", *International journal of Electrical Power and Energy Systems.* vol. 24, no. 10, 807-813.

[9] VSC. Lim, JDF. Mcdonald, TK. Saha, 2009, "Development of a new loss allocation method for a hybrid electricity market using graph theory", *Electric Power System Research.* vol. 79, no. 2, 301-310.

[10] E. Acha, C.R. Fuerte-Esquivel, H. Ambriz-Pérez and C. Angeles-Camacho, 2004, *FACTS: Modelling and Simulation in Power Networks*, Wiley, 311-340.

[11] S.M. Abdelkader, 2007, "Allocating transmission loss to loads and generators through complex power flow tracing", *IET. Gener.Transm.Distrib.*, vol. 1, no. 2, 584-595.

[12] Gephi: network analysis and visualisation tool. Available online: http://gephi.org/.

[13] Ecotricity. Available online: Available online: http://www.ecotricity.co.uk/.

[14] Y. Zhou, and K. Gurney, 2010, "A new methodology for quantifying residential and commercial fossil CO_2 emissions at the building spatial and hourly time scale", *Carbon Management.* vol. 1, no. 1, 45-56.