Visualizing CO_2 to Account for Emission Obligation in Power Systems

Mahdi Rouholamini, Carol Miller, Caisheng Wang,
Mohsen Mohammadian, and Mohammadamin Moghbeli

Abstract

The electricity use is a significant part of human's environmental footprint. Fossil energy is still used as the major energy resource for power generation. Policy makers seek a remedy to mitigate carbon emissions of fossil fuels. A virtual carbon emission tracing method is discussed in this paper. This paper facilitates allotting carbon obligation in power systems.

Keywords

Carbon emission flow • Power systems • Power tracing • Proportional sharing principle

1 Introduction

A dramatic rise in human population and productions starting from the Industrial Revolution has resulted in great demand for energy, subsequently releasing into the atmosphere a large-scale quantity of carbon and causing climate change globally (Jung and Koo 2012; Kang et al. 2012). Therefore, a considerable number of research studies have been conducted in recent years on low-carbon technologies. However, aside from the technical aspects, the methodology for evaluating the emitted amount of emission is also of vital importance in low-carbon development and for setting up appropriate emission-related policies (Kang et al. 2012). Power systems, connecting various fossil fuel-based power plants, play a key role in environmental issues. The concerns coming from electricity usage occur in the form of pollution of air and water and consequently the climate change (Munksgaard and Pedersen 2001). With regard to what has been conducted in literature, two principles regarding who is responsible for the CO_2 emitted emerge—the producer or the consumer (Marriott and Matthews 2005). The first one assumes that a significant part of the CO_2 emissions is linked to the energy production sector, mostly the power generators, and therefore, the producer is responsible for the CO_2 emissions. More recently, an increasing number of studies have asked for attention to the fact that "consumers" should also be responsible when it comes to CO_2 that is emitted at the time of the production, rather than "producers" alone (Marriott and Matthews 2005; Kang et al. 2015). Thus, this paper focuses on the relationship between carbon emissions and power consumers. The way carbon emissions are dealt with in this paper differs from the way in which they are usually treated. We consider them as a sort of carbon flow in power systems and not as a sort of greenhouse gas (GHG) emissions. The paper provides policy makers with a more tangible understanding of emission, and the results can help power utilities improve the system design and operation for the purpose of carbon emission mitigation.

2 Virtual Emission Tracing in Power Systems

In power systems, a virtual carbon emission flow can be assumed tightly integrated with the power flow (Kang et al. 2012), however, in this paper in a direction opposed to that of power, but with the same pathway as power flow (Kang et al. 2012). For example, consider a single customer–single producer system as shown in Fig. 1. The power producer is a

M. Rouholamini (✉) · C. Wang
Electrical and Computer Engineering Department,
Wayne State University, Detroit, MI, USA
e-mail: gj9598@wayne.edu

C. Wang
e-mail: cwang@wayne.edu

C. Miller
Department of Civil and Environmental Engineering,
Wayne State University, Detroit, MI, USA
e-mail: ab1421@wayne.edu

M. Mohammadian
Notashan Sanat Co., Tehran, Iran
e-mail: mohammadian@notashan.com

M. Moghbeli
University of Politecnico di Milano, Milan, Italy
e-mail: m.moqbeli@gmail.com

V. Naddeo et al. (eds.), *Frontiers in Water-Energy-Nexus—Nature-Based Solutions, Advanced Technologies and Best Practices for Environmental Sustainability*, Advances in Science, Technology & Innovation,
https://doi.org/10.1007/978-3-030-13068-8_17

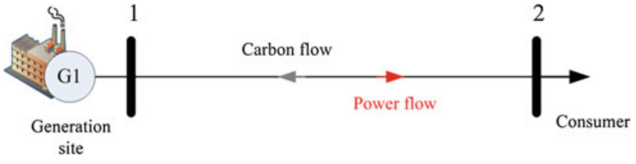

Fig. 1 A single customer–single producer system

thermal unit. He causes or "emits" a certain amount of emission. As mentioned earlier, we are to get the consumer involved in emission responsibility or at least specify how the emitted emission is affected by her behaviour. The carbon emission physically emits at generation site, leading us to assuming the direction of the virtual carbon flow opposed to that of power flow. This means that she receives some service or product in the form of electricity whose waste (or the useless part of the product) in the form of carbon emission is then sent back upstream to where the electricity was originally imported from. This virtual carbon emission travels as fast as electricity does. However, in a real-life power network, performing the above-mentioned virtual carbon emission tracing is much more complicated than Fig. 1. Therefore, we need to do power tracing first. By performing energy (or power) tracing, one can compute how much power flows from a given generator to a given load as well as determining to what degree a load or generator contributes to the power flow in a line (or branch) of the network (Kirschen and Strbac 1999; Abdelkader 2008). It is worth noting that the quality of electricity is identical throughout the system and that is why power tracing arises.

Methods to implement power tracing can be categorized as numerical and graphical (Davidson et al. 2013). Numerical methods benefit from matrix computation and are of simple algorithms. There are different methods given in the literature to perform power tracing (Kirschen and Strbac 1999; Abdelkader 2008; Wei et al. 2000; Ming et al. 2004; Achayuthakan et al. 2010; Kirschen 1997; Kuo et al. 2018; Zimmerman et al. 2011). We utilize the numerical one given in (Achayuthakan et al. 2010) as it not only accounts for the influence of transmission losses, but also can be used for systems with and without power circulating flows, and more importantly, it is quite transparent. It should be mentioned that steady-state analysis of power systems including economic dispatch and power flow equations (optimal power flow) as well as the utilized power tracing method (Achayuthakan et al. 2010) is not discussed in this paper for the sake of brevity. As an example, assume that the system under study is the IEEE 5-bus test system whose optimal power flow results are shown in Fig. 2. The system data can be obtained from MATPOWER (Zimmerman et al. 2011).

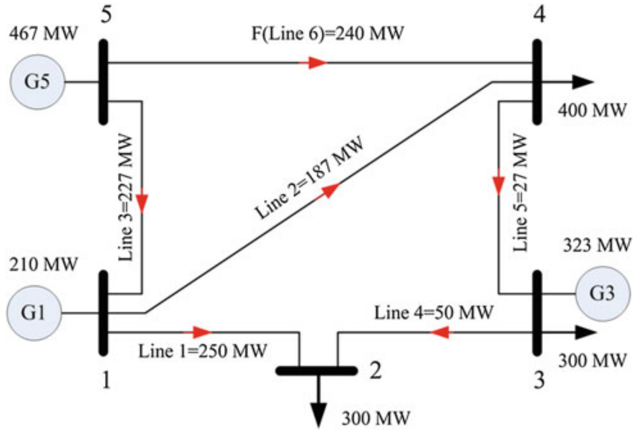

Fig. 2 IEEE 5-bus test system with optimal power flow results

Like the assumption of (Kang et al. 2015), each of the generators in the test system is considered as one of the three types given in Table 1. In case the power tracing method introduced in (Achayuthakan et al. 2010) as well as the CO_2/kWh rates presented in Table 1 is applied to the power grid benchmark shown in Fig. 2, the results will be as Fig. 3 indicates. As both the power flow (Fig. 2) and the virtual carbon emission flows (Fig. 3) in all the branches are now given, we may calculate the carbon intensity of branches and nodes. The branch carbon intensity can be defined as the ratio of the amount of carbon emission flow to the corresponding power flow. Similarly, the nodal carbon intensity is defined as the sum of all the branch carbon emissions entering a given node divided by the nodal power of the same node. These two criteria facilitate sorting the branches and nodes of the network, indicating to what degree a line or bus is clean.

3 Discussion and Conclusions

A virtual carbon emission tracing model was introduced in this paper, starting with the power tracing and then transforming electricity circulates to carbon emission flows. Although the carbon emission flows are hypothetical, meaning that they do not actually travel physically between the loads and generators, they are clearly visualized and quantified in a systematic way. The method outstandingly helps us improve our comprehension of both the emission levels of a region and how to encourage demand-side measures to prompt emission reduction. It also clearly shows to what extent the electricity being consumed at different locations is clean. Having known this spatial distribution of emissions, policy makers can set up the appropriate strategy

Table 1 Carbon emission rates of the generators (Kang et al. 2015)

Unit type	Capacity (MW)	Emission rate (kgCO_2/kWh)
Coal-fired	$C > 330$	0.875
Gas-turbine	$100 < C < 330$	0.500
Zero-emission	$C < 100$	0.000

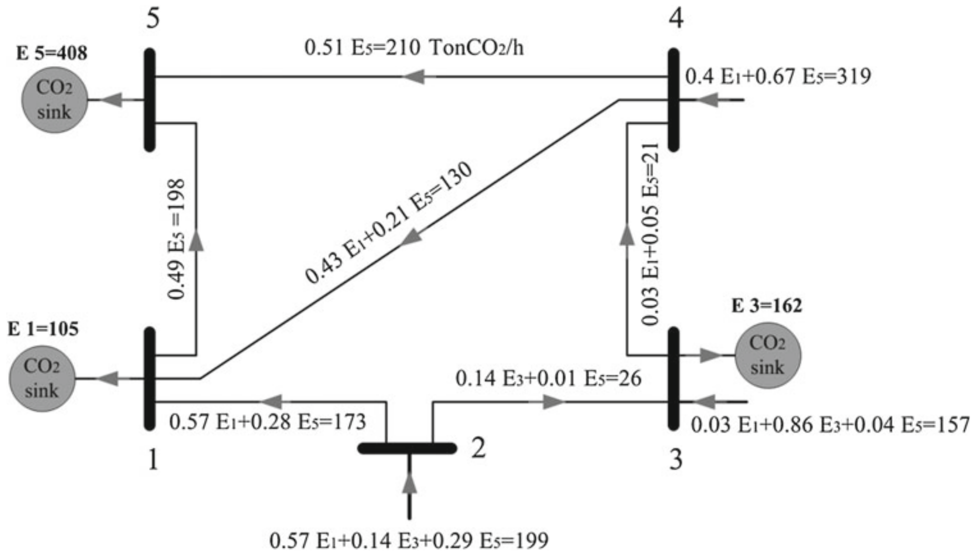

Fig. 3 The results of virtual emission tracing

to have large-scale consumers move towards load nodes with less environmental responsibility leading to the development of renewable energies. The method can also be promising for environmentally friendly and therefore sustainable network expansion planning. For example, in a power system, a transmission line that most of the time carries electricity of low-carbon intensity should be expertly taken care of when power network upgrading. In addition, by relying on the proposed method, price signals of carbon emission can be well integrated with nodal electricity prices, thereby guiding customers to best optimize their consumptions to spare money, and consequently mitigating carbon emissions. One more important advantage of the proposed method is being capable of identifying how much carbon emission has been embodied in goods and services which are not usually included in traditional methods of carbon footprints accounting. This is useful to effectively found our future carbon-trading framework, which is an emerging research topic (Lin et al. 2015; Wiedmann et al. 2016; Chen et al. 2016). The authors would like to name it "Energy-Emission Nexus" meaning how much carbon is hidden in one watt-hour at different buses of a power grid. This aspect of dialogue between producer and consumer clarifies how electricity-importing countries may covertly impose their carbon reduction obligation to the exporter ones without being charged.

References

Abdelkader, S. (2008). Determining generators' contribution to loads and line flows & losses considering loop flows. *International Journal of Electrical Power & Energy Systems, 30*(6–7), 368–375.

Achayuthakan, C., Dent, C. J., Bialek, J. W., & Ongsakul, W. (2010). Electricity tracing in systems with and without circulating flows: Physical insights and mathematical proofs. *IEEE Transactions on Power Systems, 25*(2).

Chen, G., Wiedmann, T., Hadjikakou, M., & Rowley, H. (2016). City carbon footprint networks. *Energies, 9*, 602. https://doi.org/10.3390/en9080602.

Davidson, E., Currie, R., Kwon, Y., Martínez, J., Mcneill, N., & Hey, R. (2013). Tracing the carbon intensity of active power flows in distribution networks. In *22nd International Conference on Electricity Distribution*, Stockholm, June 10–13, 2013.

Jung, T. W., & Koo, J. H. (2012). A study on U-city carbon footprint calculation method to prepare for carbon emission trading system. In *8th International Conference on Computing Technology and Information Management (ICCM)*, Seoul, South Korea.

Kang, C., Zhou, T., Chen, Q., Wang, J., & Xia, Q. (2015). Carbon emission flow from generation to demand: A network-based model. *IEEE Transactions on Smart Grid, 6*(5).

Kang, C., Zhou, T., Chen, Q., Xu, Q., Xia, Q., & Ji, Z. (2012). Carbon emission flow in networks. *Journal of Scientific Reports*. https://doi.org/10.1038/srep00479.

Kirschen, D. (1997). Contributions of individual generators to loads and flows. *IEEE Transactions on Power Systems, 12*(1).

Kirschen, D., & Strbac, G. (1999, November). Tracing active and reactive power between generators and loads using real and imaginary currents. *IEEE Transactions on Power Systems, 14*(4).

Kuo, M.-T., Lu, S., & Tsou, M. (2018). Considering carbon emissions in economic dispatch planning for isolated power systems: A case study of the Taiwan power system. *IEEE Transactions on Industry Applications, 54*(2).

Lin, J., Hu, Y., Cui, S., Kang, J., & Ramaswami, A. (2015). Tracking urban carbon footprints from production and consumption perspectives. *Environmental Research Letters, 10*.

Marriott, J., & Matthews, H. S. (2005). Environmental effects of interstate power trading on electricity consumption mixes. *Environmental Science and Technology, 39,* 8584–8590.

Ming, Z., Liying, S., Gengyin, L., & Ni, Y. (2004, April). A novel power flow tracing approach considering power losses. In *IEEE International Conference on Electric Utility Deregulation, Restructuring and Power Technologies (DRPT2004)*, Hong Kong.

Munksgaard, J., & Pedersen, K. A. (2001). CO_2 accounts for open economies: Producer or consumer responsibility? *Energy Policy, 29,* 327–334.

Wei, P., Yuan, B., Ni, Y., & Wu, F. F. (2000). Power flow tracing for transmission open access. In *International Conference on Electric Utility Deregulation and Restructuring and Power Technologies*, London, UK.

Wiedmann, T. O., Chen, G., & Barrett, J. (2016, August). The concept of city carbon maps: A case study of Melbourne, Australia. *Journal of Industrial Ecology, 20*(4), 676–691.

Zimmerman, R. D., Murillo-Saìnchez, C. E., & Thomas, R. J. (2011). MATPOWER: Steady-state operations, planning, and analysis tools for power systems research and education. *IEEE Transactions on Power Systems, 26*(1), 12–19.