Renewable and Sustainable Energy Reviews 98 (2018) 268–287

Contents lists available at ScienceDirect

Renewable and Sustainable Energy Reviews

journal homepage: www.elsevier.com/locate/rser

The role of energy from waste in circular economy and closing the loop concept – Energy analysis approach

Tihomir Tomić, Daniel Rolph Schneider*

University of Zagreb, Faculty of Mechanical Engineering and Naval Architecture, Ivana Lučića 5, 10 002 Zagreb, Croatia

ARTICLE INFO

Keywords:
Energy recovery of waste
System energy analysis
Energy consumption and production
Circular economy
Closing the loop approach
System integration

ABSTRACT

Security of energy supply and the threat of climate change are the key challenges that define the further development of EU energy systems. The security of supply problem follows other problems such as energy and material scarcity, import dependency and waste generation. These problems can be alleviated via development of a low-carbon, sustainable, competitive and resource-efficient economy. One of the pillars of this approach is a circular economy and "closing the loop" approach. Integrated waste management system can close the loop, not only material-wise, through material recovery, but also energy-wise, by using energy from waste to drive whole waste management and recovery chain. Such approach is utilized in this paper through tracking of each energy vector and calculating coverage of energy needs inside the analysed systems. Energy analysis is accepted approach for sustainability assessment of the various products and systems, where primary energy consumption approach is mostly used. By combining these two approaches, the impact of closing the loop material- and energy-wise on the sustainability of the recycled materials is assessed by analysing to which degree can the embodied energy of recycled materials be reduced. The results of the analysed city case study show that energy recovery can satisfy up to 60/50% (in 2020/2030) of the total energy needs of the analysed system; in 2030 38% of waste routed to energy recovery (from which 25% to anaerobic digestion and the rest to the incinerator) satisfies around 50% of energy needs. This internal (partial) coverage of systems energy needs can additionally reduce embodied energy of recycled materials, and increase their sustainability (primarily lowered by material recovery) by 11–67% at the same time. From these results it can be concluded that energy recovery of waste could help to "close the loop" in the whole waste recovery mindset.

1. Introduction

The increasing economic activity and corresponding raw material consumption during the last century has led to (material and energy) import dependence [1] and emphasised waste management (WM) problems in the EU. Today, the EU generates over 1.8 t of waste per capita (excluding mineral wastes), 27% of which is Municipal Solid Waste (MSW) [2]. These problems are especially highlighted in urban areas with a high population density. With around 75% of its population and GDP generating activities located in the urban areas, Europe can be called "a union of cities and towns" where urbanisation impacts and associated problems extend beyond city borders, on the EU as a whole [3,4]. At the same time, cities consume about 60–80% of energy and emit about the same amount of CO_2 on the global level [5].

The EU has recognised the problems of energy supply and climate change as one of key challenges. In order to tackle with these issues, the European Commission adopted the 2020 Climate and Energy Package [6] (Directives 2009/29/EC [7], 2009/28/EC [8], 2009/31/EC [9] and Decision No. 406/2009/EC [10]) and the 2030 Climate and Energy Framework [11] which builds on the 2020 Climate and Energy Package and is in line with the longer term perspective set out by Roadmap for moving to a competitive low-carbon economy in 2050 [12], the Energy Roadmap 2050 [13] and the Transport White Paper [14]. This path includes a reduction of GHG emissions by 80% (below 1990 levels) by 2050, in which all sectors need to contribute. To achieve these goals, the power sector should become almost carbon neutral and heating

Abbreviations: AD, anaerobic digestion; BW, bio-waste; CHP, combined heat and power; CNG, compressed natural gas; CED, cumulative energy demand; EE, embodied energy; EfW, energy-from-waste; GHG, greenhouse gas; ISO, International Organization for Standardisation; LCA, life cycle assessment; LHV, lower heating value; MBT, Mechanical Biological Treatment; MSW, municipal solid waste; MW, mixed waste; PE, primary energy; RDF, refuse derived fuel; UPR, unit process data; WM, waste management

* Corresponding author.
E-mail addresses: tihomir.tomic@fsb.hr (T. Tomić), daniel.schneider@fsb.hr (D.R. Schneider).

https://doi.org/10.1016/j.rser.2018.09.029

Nomenclature

E	energy flow
Ec	energy consumption
Ep	energy production
M	material flow
mo	material mass
mo_uk	material output
W	waste flow

should be based on renewable electricity (including biowaste) or other low-emission sources. Transport emissions should be reduced by more than 60% by 2050 using biofuels (e.g. Waste-to-Biomethane concept) and electrification, while it is planned that fossil fuels are substituted with electricity and renewables for heating and cooling in the building sector. Along with this path, Heat Roadmap Europe [15,16] emphasises the importance of district heating in meeting EU goals, identifies the positive influences of local energy sources on EU energy systems and classifies waste as the primary heat source for district heating. How to transform the EU economy into a sustainable one till 2050 is outlined by the Raw Materials Initiative [17] and the Flagship Initiative for a Resource Efficient Europe [18]. This path includes increasing resource productivity and decoupling resource (including energy) consumption and environmental impact from economic growth. On this basis, the “transformation within a generation – in energy, industry, agriculture, fisheries and transport systems, and in producer and consumer behaviour” is proposed by the Roadmap to a Resource Efficient Europe [19] where Circular Economy is identified as the best concept by which transformation in all areas should be driven.

While the use of local waste to cover local energy needs seems as an ideal synergy, waste can also alleviate the problem of material shortage. Waste Framework Directive [20] defined the first step for material recovery increased by setting waste hierarchy which defines recycling as a preferred option for waste recovery, while energy recovery is subordinated to it. Circular Economy Package [21] made the next step by increasing MSW primarily separation targets. Also, Circular Economy introduced "closing the loop" concept of material/product lifecycle and measures that cover the whole life cycle of material from production and usage via disposal and WM to market for recovered resources and recovery. “Closing the loop“ between the end of the life of the product and its production enables circulation of resources, materials and products and keeps its energy, material and economic value within the economy for as long as possible. One of the results of the implementation of these regulations in national legislation is the change in available quantities of waste for use in Waste-to-Energy/Waste-to-Biomethane systems [22,23].

As it can be seen, material and energy related legislation considering sustainable development are segregated while striving for the same goal. The Circular Economy Package puts more emphasis on closing the loop on the material side. Because of this, developed Circular Economy model [24] is taking into consideration only pollution and recyclable material input, next to economic parameters. Model concludes that economic growth alone cannot maintain/improve existing environmental quality (contrary to waste Kuznets Curve [25]) and to do so the recycling ratio needs to be increased. Influence of material recovery is analysed in many papers. In [26] closing the loop in aluminium cans industry showed that the increase in recycled share increase decreases the environmental impact of material production. This is further analysed in [27] by comparing can-to-can closed-loop manufacturing for recycling mixed post-consumer aluminium packaging. This is expanded in [26] which also took into account the use of renewable energy sources. Closing the loop of plastic waste production is elaborated in [28] and different approaches to its recovery are analysed: closed, semi-closed and open loop recycling as well as incineration.

Energy carriers produced from wastes are a part of urban energy systems – DH, electricity, natural gas and also transport system. They replace primary energy carriers which leads to partial fuel shift. Because of their interdependence, WM planning needs to be conducted in cooperation with the energy system and urban planning. Produced energy carriers can be used for powering WM system on local (city scale) or wider (system scale) level which makes a step further in "closing the loop" concept introduced by the Circular Economy Package. Due to this, energy systems development [29], resource management [30], and the coupling of urban waste and energy systems [31], have been previously analysed. Also, energy-from-waste (EfW) potentials and possible GHG emission reduction by anaerobic digestion (AD), incineration, and pyrolysis-gasification are assessed in [32] and wider Life Cycle Assessment (LCA)-based analyses of different WM systems was conducted in [33,34], but only electricity generation was considered. LCA analyses of province WM systems with the emphasis on primary waste collection/separation and residual waste recovery are given in [35,36]. Many papers cover potential energy production from MSW, especially in urban areas, but they mainly put the focus on electricity production. The exemption is [37] where LCA-based analysis of WM system with biogas upgrade is conducted, but only to evaluate potential use in transport. Temporal changes in quantity/composition of waste streams were not addressed in previous papers. Overview of EfW potentials and technologies alone is given in [38], but not as a part of integrated WM systems. Unlike other papers, it took into account changes in the waste amount and produced energy. A Waste-to-Biomethane techno-economic assessment in the urban environment, by addressing important links and synergies between waste and transport sectors is given in [39]. That paper also compasses alternative of biogas injection into a gas grid was but no interactions with other technologies were analysed.

Integrated WM systems were analysed by many aspects. While no criteria can be ignored, the European Commission emphasised LCA as the “best framework for assessing the potential environmental impacts of products” [40]. LCA methodology for environmental impacts assessment was introduced four decades ago [41]. From the beginning, consumption of PE, has been reported in LCA studies as one of the key indicators [42]. PE consumption indicator, also called CED, has also been a part of engineering guidelines (German VDI [43] and Swiss SIA [44]) and in European construction standards (EN 15804 [45], 15978 [46] and 15643-2 [47]). ISO mentions depletion of fossil energy resources as impact category in ISO/TR 14047 [48] although energy indicator is not required by its LCA standards. CED is used to display the overall PE consumption of analysed product production. It takes into account the overall production chain, i.e. all front-end processes. Despite its popularity, CED is defined and used in different ways because of a lack of standardisation. Some of the questions related to using CED as an indicator are: does it distinguish (and does it need to) different energy vectors, which energy vectors (inputs) does it encompass, how is energy value of each energy vector defined, does it need to include energy and material consumption of energy sources and does it examine FE demand or PE aspect of resources [39]? Approaches to the calculation of the CED vary depending upon the answers to these questions.

CED is also a proxy to assess environmental impact, correlates with more complex single-score life cycle impact assessment methodologies [49,50] and can be used as an energy related indicator for screening of LCA [51] which makes it an appropriate decision-making tool [52]. It is reported in Ecoinvent [53] database as an impact category indicator for all flows. The approach used to calculate CED includes the use of resources and their intrinsic value by analysing the use of fossil, nuclear and renewable energy sources. Renewable energy production/usage is defined by the energy harvested approach, chemical energy through its higher heating value and fission energy as uranium consumption multiplied by its energy value [54].

Energy approach is used in many published papers. Energy cycle