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Current and future prospects for heat recovery from waste in European district heating systems: A literature and data review

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Keywords

Municipal solid waste, Waste-to-Energy, heat recovery, district heating, European Union

List of abbreviations

4DH	Strategic Research Centre for 4th Generation District Heating Technologies and Systems
CEWEP	Confederation of European Waste-to-Energy Plants
EEA	European Environment Agency
ETC	European Topic Centre
IEA	International Energy Agency
IEE	Intelligent Energy Europe
ISWA	International Solid Waste Association
IVL	Swedish Environmental Research Institute
MS	(EU) Member State
MSW	Municipal Solid Waste
NUTS2	Nomenclature of Territorial Units for Statistics, 2nd level
RDF	Refuse Derived Fuels
WTE	Waste-to-Energy

Abstract

Municipal solid waste has seen increasing annual volumes for many decades in contemporary Europe and constitutes, if not properly managed, an environmental problem due to local pollution and greenhouse gas emissions. From an energy perspective, waste is

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also an alternative fuel for power and heat generation; energy recovery from waste represents an effective measure to reduce landfilling and avoid disposal emissions while simultaneously reducing the equivalent demand for primary energy supply. A key factor for obtaining the full synergetic benefits of this energy recovery is the presence of local heat distribution infrastructures, without which no large-scale recovery and utilisation of excess heat is possible. In this paper, which aims to estimate municipal solid waste volumes available for heat recovery in European district heating systems in 2030, a literature and data review is performed to establish and assess current and future EU waste generation and management. Main conclusions are that more heat can be recovered from current Waste-to-Energy facilities operating at low average heat recovery efficiencies, that efficient incineration capacity is geographically concentrated, and that waste available for heat recovery in 2030 is equally determined by total generation volumes by this year as by future EU deployment levels of district heating.

1 Introduction

Generation of waste is a symbiotic, unfortunate, and potentially detrimental consequence of producing and consuming material goods and services in the world today. Waste, furthermore – if not treated properly – endangers the sanity of local environments, affects the equilibrium of regional and global ecosystems, and may eventually threaten the very foundation for healthy and sustainable life conditions in any community [1-4]. For this reason, waste management represents a critical societal function needed to meet the challenges raised by generated waste flows, be they municipal solid wastes (MSW), industrial wastes, or any other kind of material residues.

In the European Union (EU) context, these circumstances has been apprehended for at least half a century and plausible approaches and solutions to reduce total generation volumes, as well as to arrange proper management measures to treat these, have been conceived and formulated in environmental action programmes [5, 6], in legislation [7-11], and in numerous projects and studies [12-19]. Most urgent, as it represents the least attractive waste management option due to e.g. uncontrolled greenhouse gas emissions, has been efforts to reduce landfilling and land deposits (expressed as early as 1999 in the so called Landfill Directive [20]), an unfortunate practice among EU Member States (MS) still accounting for nearly 40% of MSW treatment in 2010 [21]. More profoundly, in the recognition of latent interdependencies between waste generation, population growth, and economic activity, the idea of decoupling human well-being from virgin resource use (resource decoupling) have constituted the ground foundation of EU waste policy for the last couple of decades.

If not by landfilling then, according to the principles outlined in most recent EU waste legislation, the Waste Framework Directive [22], waste management should consist of not one, but many different treatment options reflecting the characteristics and properties of different waste fractions, and should ideally be initially prevented or minimised. In order of preference, treatment options should moreover be arranged in the following priority order: re-use, recycling, composting, incineration (with and without energy (and heat) recovery), and – when all other options are exhausted - landfilling (deposit). To underline this fundamental strategy for the coming years, a revision of current EU waste legislation has been suggested in 2013 [23] and a proposal for a new coherent waste management policy aligned with the overarching concepts of a circular economy [24, 25] and an energy union [26] is now under discussion [27].

With this clear aim for future European waste management to move "up the waste hierarchy" one immanent, topical, and unneglectable issue concerns the forthcoming fate of energy recovery from waste, or Waste-to-Energy (WTE) [28-30]. It is understood that, in a realised circular economy future, no or little recyclable waste fractions should remain available for this definitive conversion of materials into electricity, heat, flue gas and ashes (at least not non-hazardous fractions), so it is fair to wonder what waste volumes eventually will be left for energy recovery in view of these ambitions?

As will be further investigated and presented in this paper, this question may however not be entirely answered merely by correctly forecasting future European waste generation volumes (which in itself is an arduous and, by nature, speculative undertaking), nor by justly interpreting the scope and credibility of future waste legislation targets. The equitable answer need as well to consider the future development of more energy efficient supply structures for the provision of space heating and domestic hot water in European buildings. If this development is to be characterised by a comprehensive and continued expansion of district heating systems (mainly in urban areas), as outlined and discussed amongst others in [31-34] and modelled inter alia in [35-37], the European community will have gained additional access to necessary infrastructures by which to facilitate heat recoveries from waste designated to energy recovery.

Such a development, however, is by no means given for Europe of tomorrow, despite ambitious legislation to bring forth national heating and cooling plans, heat and cold synergy mapping, and improved structural energy efficiency, as mediated inter alia in the Energy Efficiency Directive of 2012 [38, 39]. As will be discussed further in this paper, European district heating has, on average, evolved markedly in absolute terms during the last 20 years, especially so in commercial and public service sectors, but not significantly so in relative terms – and not coherently so in terms of geographical distribution. This latter circumstance itself has an indirect influence on future prospects for heat recovery from waste since a continued disproportionate distribution of heat recovery infrastructures may reflect in an as well skewed distribution of efficient WTE facilities, hereby perhaps intensifying an already untenable situation of continental exports and imports of waste. Possible magnitudes of future European heat recoveries from WTE activities must therefore be conceived as a consequence of several prospective developments, where e.g. behavioural, demographical, economic, political, but, not least, infrastructural dimensions of society all appear significant.

The main aim of this paper is to add perspective and some clarity as to what can be expected of European heat recovery from waste in the future, mainly by illustrating the historic development and plausible future progress of MSW generation, MSW management, and district heating deployment in Europe, as well as to discuss some contextual concerns and issues. As with all complex matters, characterised by multiple influences and mutual interdependencies, of which seldom all are identifiable and perhaps even less so quantifiable, it is appropriate first to outline an initial general overview. The purpose of this study is essentially to establish such a holistic understanding at EU MS level, hence principally devoting little or no attention to local-, technology-, or regional policy-specific issues undoubtedly related to the continental scope topics at hand. The structural nature of the questions raised in this study is rather; what general tendencies are observable in past records? What are current MS national and EU continental state of affairs? What can be expected in the future, given these historic trends, current conditions, model predictions, and outspoken ambitions for the years to come? More specifically, this paper aims to answer the following three research questions:

- What are the historical trends of MSW generation and management among EU MS from 1995 to 2012?
- What models have been developed and used in recent years to assess future EU MSW generation and district heating deployment, and what are their predictions for 2030?
- According to model predictions and scenario targets, how much MSW is likely to be available for thermal energy conversion and heat recovery in EU district heating systems in 2030?

Given the general uncertainty of future assessments, the answers presented to the latter two of these questions must be interpreted as indicative and approximate only. The purpose here is not claiming to have identified the most likely future development for European waste generation and heat recoveries from these waste flows, a development subject to several additional sector influences not considered here (e.g. changing characteristics of waste, technical changes and modifications of WTE technologies), but merely to make explicit what past and present modellers have assessed plausible. In this respect, reviewed models and associated assumptions (in the case of regression models, chosen explanatory variables), are viewed and accepted as is, and no model analyses are performed in this context. The study limitations, further, exclude any technical or commercial feasibility assessment of future WTE technologies or heat recoveries from waste in European district heating systems, estimates which despite their general relevance and interest are beyond the study scope and objective. Additional study limitations concern related waste incineration topics, such as ash deposits, air emissions (e.g. greenhouse gases), and issues concerning the production of refuse derived fuels (RDF), as well as waste trade related issues, such as gate fees, public opinion, and economic incentives. Finally, given the immense publication rate within the field of waste management during the last 25 years (a Scopus search 2015-09-15, 1990 to present, returned 4,369 articles with "waste management" in the paper title!), the literary sources referred to in this work represent a sample reflective of the study objectives rather than constituting a complete review of this ample flow.

2 Materials and Methods

The main focus in this paper is EU MSW, which in terms of total generation in recent years has hovered at around some 230 to 250 million metric tonnes (Mt) per year (EU28) [40]. For the sake of reference, however, it should be noted that the total sum of all generated waste in EU28, i.e. mineral, metal, animal and vegetal, chemical and medical, textile, glass, plastic, and sludge wastes etc., amounted to no less than 2.51 billion metric tonnes (Bt) in 2012, according to [41]. From a perspective of MSW, hence, the annual volumes considered here represents merely one approximate tenth of total generation volumes, and waste destined for energy recovery herein represents itself merely a fraction of total MSW generation. It should also be noted that current heat recoveries from MSW incineration represent less than 10% of total heat supplies to European district heating systems, which are dominated by natural gas, other bituminous coal, and primary solid biofuels.

At current, if neglecting anaerobe digestion processes, European energy recovery from WTE activities is more or less solely performed by Rankine steam cycle incineration processes, where waste is – either directly or by co-firing – burnt to generate steam and hot flue gases. Gasification of waste, associated with both pros and cons compared to incineration, e.g. an intermediate product (syngas) with a wider array of applications (e.g. fuel production), potential for higher conversion efficiency (e.g. integrated gasifier combined cycles), but syngas being toxic and potentially explosive [42], has so far seen very limited commercial use in Europe. For the future, however, gasification (and pyrolysis) of waste may very well become a challenger in European WTE, considering additional benefits such as reduced generation of pollutants (dioxins and NO_x), lower operation temperatures, and more efficient material recovery, e.g. metals [43-45].

Consisting in essence of incineration facilities only then, the stock of designated EU WTE plants currently in operation (2011) was assessed in 2013 as a sub-task during the second EU pre-study of the Heat Roadmap Europe project [46, 47]. As outlined in Fig. 1, this estimation, which aligned all reported EU28 plants in the 2012 ISWA State-of-the-Art Report (397) [48] with georeferenced facilities reported in the European Pollutant Release and Transfer Register [49], while using as well some additional sources [50, 51], identified 432 facilities with geographical location and annual incineration capacity. The total annual incineration capacity of these facilities was assessed to ~86 Mt, and, as can be seen in Fig. 1, the majority of these facilities are located in Central and North-Western EU Members States.

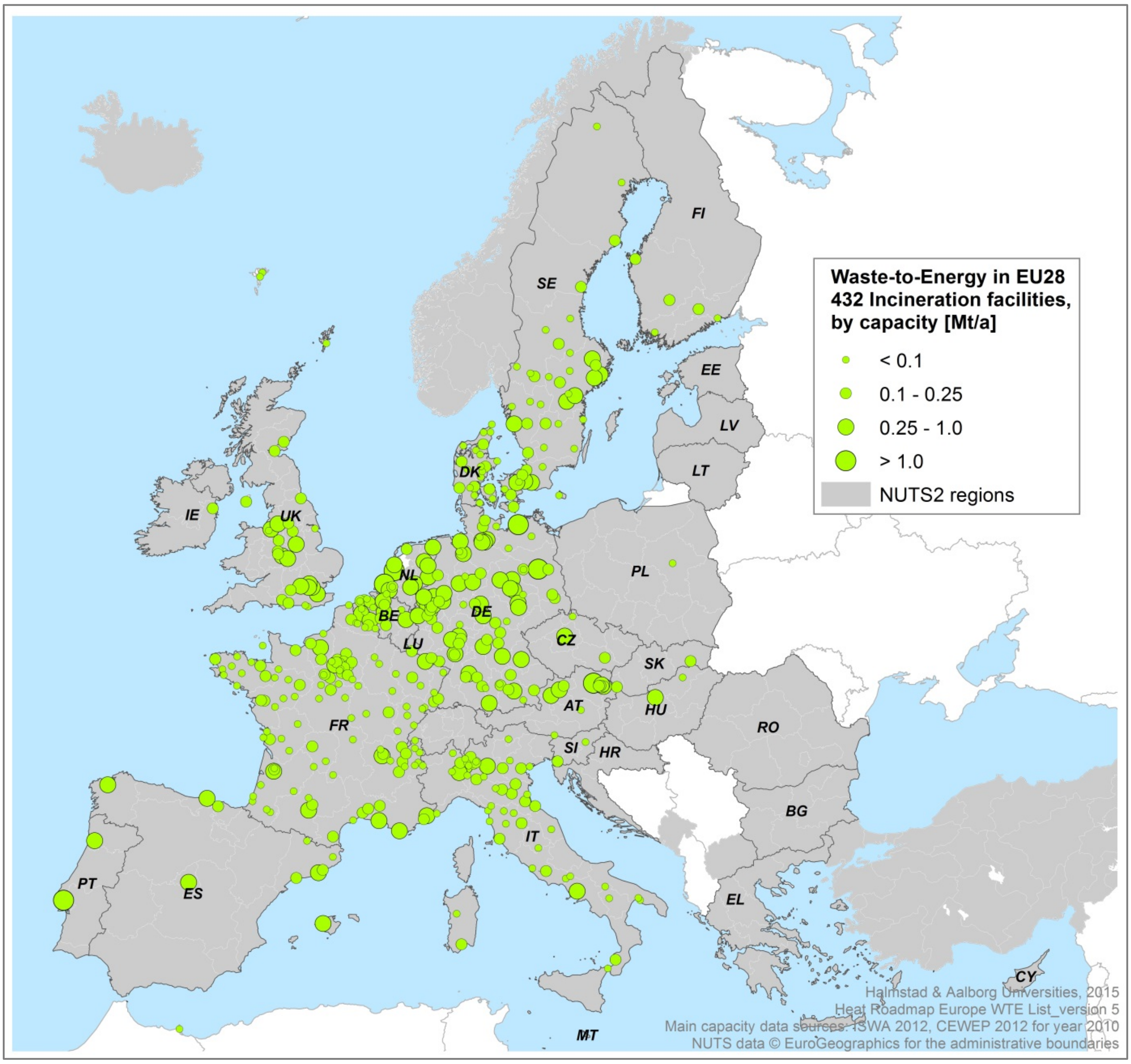

Fig. 1. 432 designated EU28 waste incineration facilities in operation during 2011, by location and by assessed annual capacity. Result from the 2nd European pre-study in the Heat Roadmap Europe project (2013). Sources: [46-51].

As established in the Confederation of European Waste-to-Energy Plants (CEWEP) report [52], the average energy content of European MSW is ~10 GJ/t, expressed as net calorific heat value. If accepting this value as a general conversion factor, the Heat Roadmap Europe assessment is well in consonance with 2010 primary energy and energy recovery volumes from waste reported in the extended energy balances of the International Energy Agency (IEA). Herein [53], total primary energy supplies from industrial and municipal (renewable and non-renewable) waste flows destined for energy conversion summed up to 800 PJ in this year, hence equivalent to ~80 Mt. If neglecting industrial waste (152 PJ), the two fractions of municipal waste represented all together 648 PJ (333 PJ renewable and 315 PJ non-renewable), which would correspond to some 65 Mt in total under given assumptions. By a municipal waste electricity output of 119 PJ and a heat output of 159 PJ, it is fair to anticipate an average overall conversion efficiency of 43% and a heat recovery efficiency of 159 PJ/648 PJ=0.245≈25% from EU MSW incineration (quota of recovered heat and primary input, see [32, 36] for further references).

And the concept of conversion efficiency truly lies at the heart of European WTE today, since the R1 formula (a performance indicator of waste incineration facilities), was introduced in the Waste Framework Directive in 2008. Taking into consideration both electricity and heat output from WTE conversions, and accentuating generated electricity by a factor 2.6 (and generated heat by a factor 1.1), the total energy yield is weighted against the energy content of the combusted waste [54]. By this regulation it has become possible for efficient WTE plants to be classified as "energy recovery" operations (R1) rather than "waste disposal" activities (D10), by achieving an efficiency higher than 0.6 (for plants in operation before 2009-01-01) and higher than 0.65 (after 2008-12-31). In 2009, around 66% of European WTE plants were classified as recovery plants, according to the formula [52], and among multiple benefits for these facilities can be mentioned e.g. lower taxes, access to imported waste (without violation of proximity and self-sufficiency principles), and eased admission to bank finance [55]. Albeit the pronounced promotion of generated electricity, and as well allowance to include some on-site used energy output in the calculation, achieving the R1 efficiency factor is more viable if having cogeneration options available compared to electricity only generation.

2.1 Past and current waste generation and management

The data used to assess historic developments and current conditions in this study are all publicly available statistics from Eurostat. These include time series data from 1995 to 2012 on EU MS MSW generation and management [40] and national and NUTS2 regional total population counts [56]. On NUTS2 regional level, corresponding MSW generation data has been made partly available by a promising – however yet to reach full continental stretch – pilot project covering the years from 2000 to 2011 [57], which also comprises precious data on number and capacities of recovery and disposal facilities at this regional level [58].

By use of this information, specific MSW volumes for EU28 and its MS during 2012 are illustrated in Fig. 2. This figure is similar in arrangement to the 2008 projection presented by Persson and Werner in 2012 [59], and by comparison it can be observed that average EU MSW per-capita volumes has decreased from approximately 520 kg/capita (EU27, 2008) to ~475 kg/capita (EU28) during these five years. In terms of waste management, however, landfilling still constitutes the largest treatment option share in relative terms (34%), but it is noteworthy that the corresponding share was 40% in 2008.

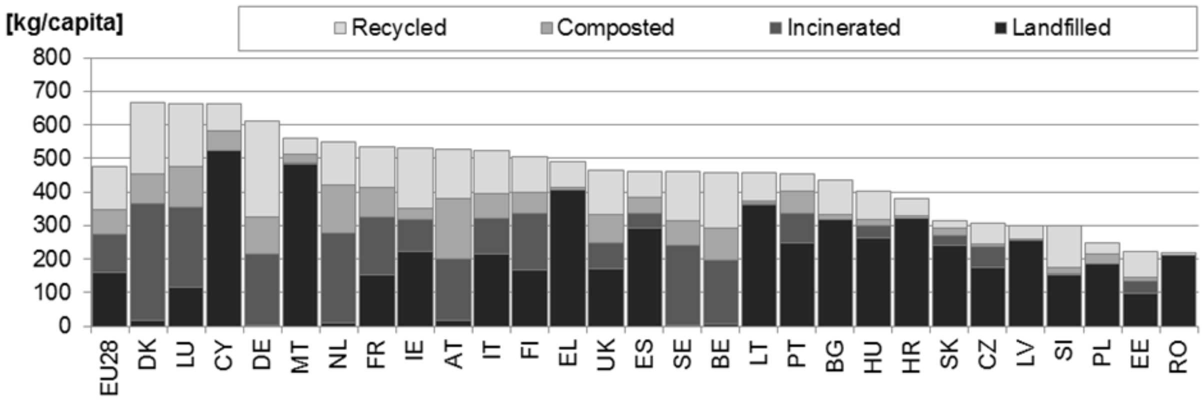

Fig. 2. Distribution of municipal solid waste treatment in EU28 Member States in 2012, by waste hierarchy order categories. Source: [40, 56].

2.2 Future waste generation and model scenarios

To facilitate an assessment of future European MSW generation and management, mainly so for the year 2030, a literature review was performed by which to learn more about what typical approaches, models, and projections, have been conceived and developed in a devotion to this purpose during recent years. Dating back to the early 1990s, aggregated US industry sector waste generation was modelled by Ayres et al. [60, 61] using material balances, a methodological approach attentive of the mass difference between commodity inputs (materials, substances etc.) and corresponding commodity outputs from considered sectors (see also the Leontief input-output economic model [62]). Simultaneously, in Europe, extending from the input-output approach, general equilibrium model applications by, for example, Alfsen et al. [63, 64] and Conrad [65], embraced environmental, emission, and energy system dimensions into the modelling (hence considerably widening the analytical scope), a discourse essentially originating in earlier works of e.g. Johansen [66, 67], Edmonds and Reilly [68, 69], and others [70-73].

In 1997, a novel study by Bruvoll and Ibenholt [74], targeting Norwegian manufacturing industry, presented national projections of solid waste generation by use of a macroeconomic model, i.e. a computational multi-sectoral equilibrium model. Considering aspects such as technological change, price substitution (value of resources vs labour), and other key economic variables, they anticipated a total 64% increase of waste generation between 1994 and 2010. In Sweden, computational general equilibrium models were later developed and used by Östblom et al. [75-77], principally based on assuming direct linkage between waste generation and economic activity of firms and households; future waste generation hence being reflected in economic growth and the relative use of production factors. This approach, the so-called EMEC model, was also used by the Swedish Environmental Research Institute (IVL) in 2010 to model future national waste generation volumes in 26 industrial sectors, the public sector, and in Swedish households [78].

Still within, and inherently rooted to, classical economic theories, another generation of models adhered to the principal idea of relating waste generation to e.g. economic activity and population growth, but, as they utilise econometrics, with a conceptually different methodological approach. Statistical investigations and models, by means of simple or multiple regression analysis, characterised this new vein of European studies emerging in the early 2000s – and especially so constant elasticity models, characterised by generating relative parameters and outcomes [79]. Through a series of reports and book chapters [80-82], the Copenhagen based European Topic Centre (ETC) developed and presented, in 2007, an econometric European model for waste and material flows [83], later also used to produce EU27 MSW generation and treatment predictions for 2020; the ETC 2008 [84] and ETC 2011 [85] projections.

By 2014, after an institutional name change to the Copenhagen Research Institute, the ETC model was incorporated in the mass flow module of the “European Reference Model on

Municipal Waste Generation and Management", developed for the European Commission and the European Environment Agency (EEA) [86, 87]. This model (hereafter referred to as the "EU Ref. model"), projects EU28 MSW waste generation up to year 2030 and is structured as a set of operational modules considering a wide range of influential conditions (e.g. prevention, collection, employment, financial costs, environmental impact etc.). A thematic overview of notable model approaches reviewed in this paper are presented in Table 1, which also includes the 2010 Arcadis/Eunomia bio-waste projection for EU27 up to year 2020 (including as well a projection of total MSW generation by this year) [88].

Table 1. Examples of notable waste generation model approaches developed and used during the period 1994 to 2014, by principal model type, flow, and projection year

Author/Name	Published	Model type	Flow	Target	Year	Reference(s)
Ayres et al.	1994	Input/Output	Ind.	USA	-	[60, 61]
Bruvoll & Ibenholt	1997-2003	Gen. equilibrium	Ind.	Norway	2010	[74, 89]
Östblom et al.	2006-2010	Gen. equilibrium	Ind./MSW	Sweden	2030	[75-77]
Sundquist et al.	2010	Gen. equilibrium	Ind./MSW	Sweden	2030	[78]
Møller Andersen et al.	2005-2011	Econometrics	MSW	EU27	2020	[80-85]
Arcadis/Eunomia	2010	Mathematical	MSW	EU27	2020	[88]
EU Ref. model	2014	Econometrics/Modules	MSW	EU28	2030	[86]

As the most recent, comprehensive, and only EU model assessment extending to 2030, the EU Ref. model is used in this work as the key benchmark trajectory by which to evaluate plausible prospects for future European heat recovery from waste. Appropriately, for this aim, the baseline and five scenario projections elaborated in the model [86], as tabulated in Table 2, provide a suitable framework for the study analysis. Current legislation, i.e. the Waste Framework Directive, stipulates a 50% recycling, or preparation for re-use, target for EU MS by 2020, and, correspondingly, the majority of MS shall have accomplished a 35% landfill limit by 2016 according to the Landfill Directive. It is likely that current revisions of these regulations will propose much more stringent targets; perhaps as high as 80% recycling shares and complete landfill bans for all recyclable and biologically degradable wastes. Given these circumstances, Scenario 4 from the EU Ref. model assessments, i.e. 70% recycling and a 5% landfill limit by 2030 (highest ambition level), constitute the reference case used here.

Table 2. Baseline (Business-as-Usual) and five scenarios evaluated by the EU Ref. model on waste generation and management, 2014. Sources: [20, 22, 86, 90]

	Description	Recycling/Preparation for reuse target	Landfill limit	By year
Baseline	Steady state waste management	-	-	-
Scenario 1	Full implementation of existing targets	50%[a]	35%[b]	2020/2016
Scenario 2.1	Increased recycling, no limit on landfill	60%	-	2030
Scenario 2.2	Further increased recycling, no limit on landfill	70%	-	2030
Scenario 3	Full implementation of existing targets, landfill limit	50%[a]	5%	2020/2030
Scenario 4	Further increased recycling, landfill limit	70%	5%	2030

[a] Referring mainly to household waste as expressed in the Waste Framework Directive.
[b] Referring to biodegradable municipal waste fractions as expressed in the Landfill Directive. For MS that had >80% landfilling in 1995, the target year is extended to 2020.

2.3 European district heating

Until recently, there have been very few continental assessments regarding number, distribution, and energy magnitudes of European district heating systems. In 2006, the Intelligent Energy Europe (IEE) supported project Ecoheatcool [91], presented a comprehensive estimate based on energy statistics from the IEA, where reported sold heat was interpreted, principally, as district heat. For 1992 and 2003, the study concluded that district heat deliveries amounted to 1.86 EJ and 1.76 EJ (EU25), respectively, indicating a slight decrease – in absolute terms – during the time span considered. In the case of number and distribution, it has been apprehended during the development of the Halmstad University District Heating and Cooling database [92] that some 6000 systems currently are in operation (see also [91]), and that these systems are fairly wide spread among MS (for a map on geographical locations of EU district heating systems, see [36]).

More recently, as detailed in e.g. [32, 93], district heating has been anticipated to represent ~12% of the EU residential and service sector heat market (still heavily dominated by fossil fuels, e.g. natural gas), and consisted of ~1.6 EJ out of a total final heat demand of 13.1 EJ in 2010, according to the up-to-date Stratego assessment [37]. The winter season in 2010, however, was considerably colder than an average year, why a weather-corrected comparison of 1995 and 2012 data was performed. Assuming, as in [91], that reported heat sales in the IEA energy balances [94] represent district heat deliveries, and by use of Eurostat reported heating degree-day statistics for the time period 1980 to 2009 [95-97], a more comparable assessment of EU28 and MS district heating developments is presented in Table 3. In relative terms, and keeping in mind some minor deviances in terms of MS heating degree-day calculation practices, EU district heating has on average expanded by 20% during the considered time-period, especially so in service sectors, albeit with large national variations. Since some constituents of the heat demand (domestic hot water and industrial process heat) are weather independent (not compensated for here), this comparison serves however merely an indicatory purpose. Noteworthy, the average drop in heating degree-days has been 16-18 units per year since 1980.

Table 3. Weather corrected district heat deliveries to residential, service and industrial sector buildings in 1995 and 2012, by EU28 Member States. Energy volumes in [PJ/a]. Sources: [94-97]

		1995					2012					Difference [%]			
MS	HDD_A[a]	f_{HDD}[b]	Res[c]	Ser	Ind[d]	Tot	f_{HDD}[e]	Res[c]	Ser	Ind[d]	Tot	Res	Ser	Ind	Tot
AT	3,540	0.98	15	15	4	34	1.08	37	32	13	82	141	119	192	138
BE	2,830	1.04	0.9	0.6	8	10	1.13	2	4	24	30	130	671	187	210
BG	2,654	0.97	31	1	80	112	1.07	16	4	23	44	-47	268	-71	-61
CY	762	0.90	0	0	0	0	1.17	0	0	0	0	-	-	-	-
CZ	3,533	0.98	41	18	91	150	1.09	47	20	29	96	14	10	-68	-36
DE	3,199	0.98	291	0	69	360	1.10	156	89	234	478	-46	-	238	33
DK	3,438	0.97	59	26	4	89	1.13	78	36	5	120	32	42	18	34
EE	4,393	1.04	23	1	2	26	1.08	15	5	2	22	-32	264	-8	-14
EL	1,642	1.00	0	0	0	0	1.09	2	0	0	2	-	-	-	-
ES	1,831	1.20	0	0	0	0	1.09	0	0	0	0	-	-	-	-
FI	5,774	1.02	82	0	9	91	1.09	124	0	71	195	52	-	655	115
FR	2,459	1.03	24	0	0	24	1.11	75	34	8	116	214	-	-	389
HR	2,561	0.96	5	0.8	4	10	1.11	6	2	2	11	17	117	-37	5
HU	2,886	1.00	32	17	5	54	1.08	24	7	14	45	-25	-61	205	-17
IE	2,871	1.07	0	0	0	0	1.12	0	0	0	0	-	-	-	-
IT	1,949	1.01	0	0	0	0	1.15	35	5	124	164	-	-	-	-
LT	4,048	1.02	35	8	7	51	1.08	22	9	10	41	-36	8	31	-19
LU	3,164	1.01	0	0	0	0	1.13	0	3	1	3	-	-	-	-
LV	4,220	1.03	26	11	2	39	1.08	17	6	0.3	24	-33	-42	-86	-38
MT	543	1.21	0	0	0	0	1.40	0	0	0.1	0.1	-	-	-	-
NL	2,854	1.01	7	12	55	74	1.14	12	24	51	87	71	107	-9	17
PL	3,574	0.99	263	23	77	363	1.08	195	43	32	269	-26	89	-59	-26
PT	1,278	1.39	0	0	2	2	1.09	0.3	1	15	16	-	-	588	645
RO	3,092	0.98	131	0	51	183	1.08	43	11	13	66	-67	-	-75	-64
SE	5,387	0.98	80	51	14	145	1.09	125	62	19	205	56	22	30	41
SI	3,024	0.99	4	4	1	9	1.09	4	2	2	8	-2.8	-42	109	-3.7
SK	3,416	1.00	16	12	1	29	1.08	22	6	7	34	33	-53	475	17
UK	3,081	1.03	0	0	0	0	1.10	2	18	37	57	-	-	-	-
Tot	**3,000**	**0.99**[f]	**1,168**	**198**	**488**	**1,854**[g]	**1.10**[f]	**1,062**	**421**	**734**	**2,217**[h]	**-9**	**112**	**50**	**20**

[a] Average annual Heating Degree Days (HDD_A) per MS based on 1980 to 2009 time series data reported in [95, 97].
[b] Multiplier, f_{HDD}, is the ratio of HDD_A over actual HDD for the year at hand. $f_{HDD} > 1$ indicates a year warmer than the normal year.
[c] Residential sector volumes include Non-specified (other) sector heat.
[d] Reported industrial heat volumes may include some heat used on-site for internal purposes.
[e] Multipliers for 2012 established by simple linear regression of MS 1980 to 2009 time series data and extrapolated to this year.
[f] Total multipliers are fictive (reflecting the sum of MS weather corrected district heat volumes relative the sum of corresponding MS raw data heat volumes) and does not necessarily represent actual EU28 HDD factors for 1995 or 2012.
[g] Raw data for 1995: 1,874 PJ.
[h] Raw data for 2012: 2,014 PJ

In terms of future European district heating deployment levels, no formal targets, as for waste management, have so far been established. Evidence, however, that district heating could expand cost-effectively by three times compared to current levels (essentially in inner-city areas) have been provided in [31], and – partly by this rationale – future expansion levels considering 30% (2030) and 50% (2050) shares of the total EU27 residential and service sector heat market have been modelled within the Heat Roadmap Europe context [35]. As perceived herein, the potential for WTE heat recovery in district heating systems was assessed at 330 PJ (~33 Mt) in 2030 and 585 PJ (~59 Mt) in 2050. At the current, average, EU28 heat recovery efficiency (25%), such heat recovery volumes would need to correspond to total MSW volumes designated for energy conversion of approximately 132 Mt and 236 Mt, respectively. If, hypothetically, average heat recovery efficiencies were to increase to 30%, 40% or 50% in the future, corresponding MSW volumes destined for energy conversion would be respectively; 110, 83, and 66 Mt by 2030, and 197, 148, 118 Mt by 2050.

3 Results

The results presented in the following are all based on data, literature, models, and methodological approaches, as described and accounted for above, and further ordered in alignment with the initial research questions asked. Hereby, study results refer firstly to historical and current EU MS MSW generation and treatment volumes from 1995 to 2012, secondly to model predictions of future MSW generation volumes for 2020 and 2030, and thirdly to assessed MSW volumes available for heat recovery in European district heating systems by 2030. To complement the latter, an arbitrary sensitivity analysis, where the two variables; (i) predicted total EU MSW generation in 2030 and (ii) average EU heat recovery efficiency by this year, are allowed to take on alternative values.

3.1 Waste generation and treatment – 1995 to 2012

MSW generation in EU27 saw steady annual increases during the late 1990s and marked a thitherto all-time high of 256 Mt in 2002. Succeeded by a temporary decline during 2003 to 2005, new record-breaking generation volumes were once again recorded in 2006 (258 Mt) and 2007 (260 Mt), to be followed by marginal, but consecutive, annual declines leading up to year 2012 (see Fig. 3, at left). Whether the apparently incessant decrease from 2008 and onwards reflects genuine behavioural (or structural) changes among European citizens and communities (and if so with decisive implications for future generation volumes), is an issue resolvable only at the access of more recent data. It is clear, however, that European efforts to reduce landfilling has been expedient during the considered period; representing a drop from 143 Mt (1995) to 79 Mt (2012). This significant achievement is reflected in corresponding and coherent increases in annual MSW volumes designated for incineration, recycling, and composting. Since Eurostat statistics subdivide incineration volumes in two categories; with energy recovery (R1) and without energy recovery (D10), they provide insight into the distribution of incineration volumes by these two treatment options, see Fig. 3 at centre. Among all treatment categories, WTE with energy recovery represents the fastest growing alternative, indexing above 300 during the considered time interval.

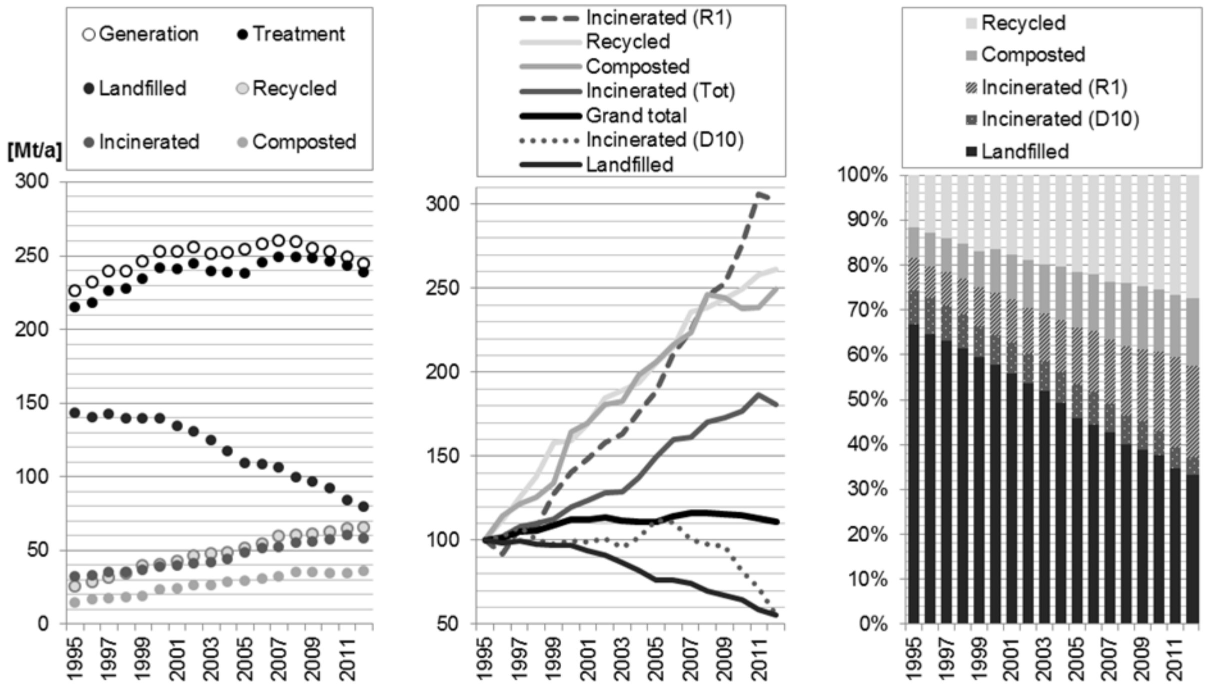

Fig. 3. EU27 MSW generation and management from 1995 to 2012. At left, total generation, treatment, and category volumes. At centre, indexed developmental trends by category with base year 1995=100. At right, relative distribution of treatment categories. Source: [40].

As illustrated in Fig. 3, at right, the relative reduction of EU landfilling further corresponds to a 34% decrease for this treatment option out of total MSW treatment volumes (67% in 1995 and 33% in 2012), which effectively confirms an average fulfilment of the Landfill Directive targets for 2016. As for the relative change of MSW volumes incinerated with energy recovery, equivalent shares out of total MSW treatment volumes were 7% (1995) and 20% (2012), while total incineration increased from 15% to 24%. Validation crosschecking of Eurostat reported MSW incineration volumes for 2010 with IEA data [53] identified smaller deviations. Possible explanations might be varying MSW definitions and counting routines among MS and perhaps incineration of MSW in e.g. cement kilns not accounted for in the Eurostat data. While summing up total incineration volumes to 57 Mt (44 Mt with energy recovery and 13 Mt without), the Eurostat data was somewhat lower than the anticipated 65 Mt (648 PJ and by conversion factor of 10 GJ/t) reported by the IEA. Since the used Eurostat data includes no information on generated heat output, hence inhibiting an estimate of heat recovery efficiency, the IEA data was chosen for this purpose.

3.2 Waste generation and treatment – in 2030

The first of four considered model predictions assessing EU MSW generation was the ETC 2008 projection. As shown in Fig. 4, at left, the trajectory proposed at this stage (projection start year 2005, EU27) anticipated total MSW generation volumes well above 330 Mt by 2020, a probable over-shoot three years later curtailed to approximately 280 Mt in the ETC 2011 version (start year 2007). The 2010 assessment of Arcadis/Eunomia arrived at a similar level (270 Mt). As if outlining maximum and minimum conditions, the three 2020 assessments seemingly mark the confines of most plausible developments for 2030, as the EU Ref. model projection stretches on to a total MSW generation volume of 308 Mt by this year (294 Mt available for management, given a historic 95.6% average ratio between generation and management in EU27 during 1995 to 2012).

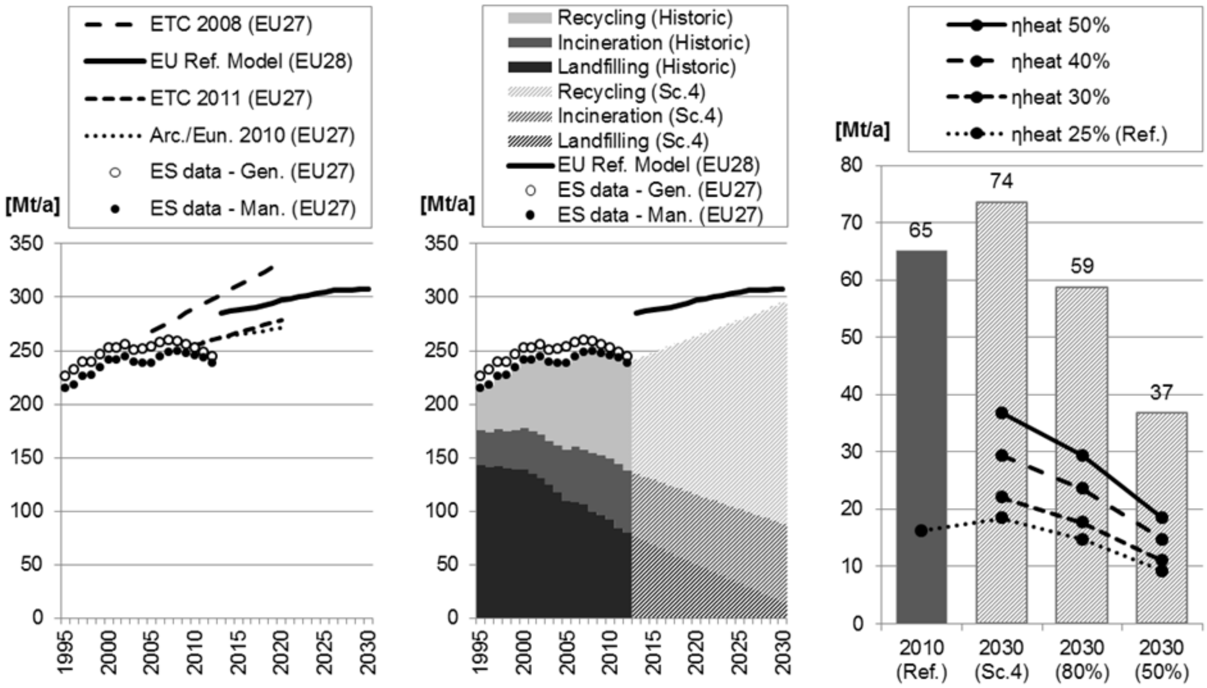

Fig. 4. At left, EU27 MSW generation and management volumes from 1995 to 2012 and four model predictions of future EU MSW generation. At centre, EU27 MSW volumes by treatment categories from 1995 to 2012 ("Recycling" including composting) linearly interpolated from 2012 to 2030 according the EU Ref. model (Scenario 4). At right, MSW volumes designated for incineration in 2010 and current heat recovery efficiency (reference) compared by sensitivity analysis to the EU Ref. model in 2030 (Scenario 4: 100%, 80% and 50%) and three levels of plausible future EU heat recovery efficiencies. Sources: [40, 53, 84-86, 88].

3.3 Heat recovery in European district heating systems in 2030

If in 2030, the EU Ref. model projections will have proven accurate, approximately 294 Mt of MSW will be available for waste management in EU28. If the European community, furthermore, manages to comply with the 4th scenario in the EU Ref. model context, 70% (206 Mt) of this manageable MSW volume will be recycled and only 5% (~15 Mt) will be landfilled. The remaining 25%, equalling 74 Mt by this year, should consequently be available for energy and heat recovery. Hereby, as presented in Fig. 4, at centre, data based 2012 levels of MSW treatment categories may be linearly interpolated to meet these anticipated 2030 volumes, hence permitting a visual representation and comprehension of the plausible distribution of EU MSW management in the years to come.

Supposing that realised conditions in 2030 arrive at only 80% (235 Mt), or merely 50% (147 Mt) of the model projection, correspondingly less MSW will be available for energy conversions (59 Mt (80%) and 37 Mt (50%), assuming constant shares), as outlined in Fig. 4, at right. Depending, however, on what average EU heat recovery efficiencies that will have been attained by this year, which itself, in essence, will be determined by materialised levels of future EU district heating deployment, actual heat recovery volumes may increase although available MSW volumes are reduced. If, in 2030, only half of projected MSW volumes will be generated (thereby leaving only 37 Mt to energy conversions), then 184 PJ may still be recovered as heat – given an average EU heat recovery efficiency of 50% (corresponding to 18.4 Mt at conversion factor 10 GJ/t).

4 Discussion

From this, it is likely that future heat recoveries from waste in European district heating systems will be determined by (at least) two independent processes; (i) the success by which decoupling of human well-being from virgin resource use is materialised, and (ii) forthcoming transition levels towards serial supply structures for the provision of building heat demands.

As for the first of these detached developments, there are today only vague indications that absolute decoupling, i.e. reduced waste generation parallel with continued economic growth, is occurring in the EU context. Mazzanti and Zoboli, who, by non-linear regression modelling (considering as well structural and socio-economic variables), evaluated the EU decoupling progress in 2008, concluded that “for waste generation there is still no absolute delinking trend” [98], see also [99]. In a Swedish study [100], Sjöström and Östblom suggested that, for absolute decoupling by 2030 (start year 2006), waste intensities linked to the three drivers technical change, economic growth, and household consumption, will need to decrease at a rate twice that of historical reduction rates, which appears not to be the case in contemporary Europe. Some indices, however, of both absolute and relative MS level decoupling of MSW generation relative economic growth, has been reported more recently in [101], in turn referring to [102-104]. Nevertheless, despite marginally more efficient domestic and raw material consumption during 2000 to 2012 (mainly in coincidence with the financial crisis of 2008), as reported in [105], European consumption patterns have in general remained highly resource intensive, which is why continued absolute decoupling must be acknowledged as posing both fundamental and structural challenges for the European community.

In this respect, let aside prevention and minimisation efforts (as, for a radical example, taxation of resources rather than taxation of labour, proposed by Bruvoll in 1998 [106]), absolute decoupling needs to imply either a shift towards more immaterial consumption, i.e. less resource intensive products and commodities, or a principally new regime in terms of European re-use and recycling. In view of current recycling levels (~27% recycling and ~15% composting, totalling at ~42% in 2012, see Fig. 3, at right), a proposition of absolute decoupling of waste generation from economic growth will in itself be contradictious unless supported by the permeate arrangement of effective, operational, and sustainable recycling technologies and infrastructures. It can therefore be assumed that a realisation of current EU decoupling ambitions will require levels of political and economic devotion, of state and municipal commitment, and of collective and individual discipline, intrinsically higher than current ones, and that this needs to be addressed and accompanied by appropriate policy and procurement measures.

As for the second process, of which much less can be said in terms of expected developmental progress since no formal targets so far has been set for EU district heating deployment, a transition towards serial supply structures on the European building heat market is as well associated with considerable economic investment. Moreover, a genuine transition of this kind, i.e. a reform towards improved structural energy efficiency, is likely to have a profound influence on traditional energy system perceptions, as well as on a wide array of technical, industrial, social, and infrastructural dimensions. In relation to WTE conversions, given their appropriate application, waste incineration with heat recovery in district heating systems is likely to represent, also in ambitious recycling and circular economy contexts, a necessary, multifunctional technology solution by which to bridge and enhance resource and energy efficiency improvements. The peculiar circumstance that (non-recyclable) combustible waste fractions, simultaneously being both a burden and an asset (residue and fuel), find their most rewarding application in such WTE conversions needs to be kept in mind when formulating future EU waste management and energy system policies.

In a recent European study by Sundberg [107], asking what role energy recovery will have in the context of increased material recycling, main conclusions are that continued access to WTE facilities are essential also at high recycling rates; namely by the ability to treat deteriorated combustible residues inevitably extending from recycling processes. Additionally, let aside generation of electricity and heat, incineration (and gasification) processes make viable the extraction of metals contained in the original waste flow, as well as the destruction of contaminated and non-recyclable fractions – all eventually contributing to a reduced demand for landfill deposits. Another key message from Sundberg, also illustrated in Fig. 2, is that MS with lowest landfilling rates at current; all have highest levels of both recycling and incineration (e.g. AT, BE, DE, DK, NL, and SE). It is clear, however, that waste incineration processes without heat recovery, not to mention without energy recovery all together, imply significantly reduced synergetic qualities of the respective treatment operations performed. To illustrate this further, see Fig. 5 (similar in arrangement to the 2008 projection presented by Persson and Werner in [108]), average 2012 EU28 MS heat recovery and absorption (electricity) efficiencies from all non-recycled MSW fractions (i.e. both incineration and landfill volumes) are depicted together with EU28 average values.

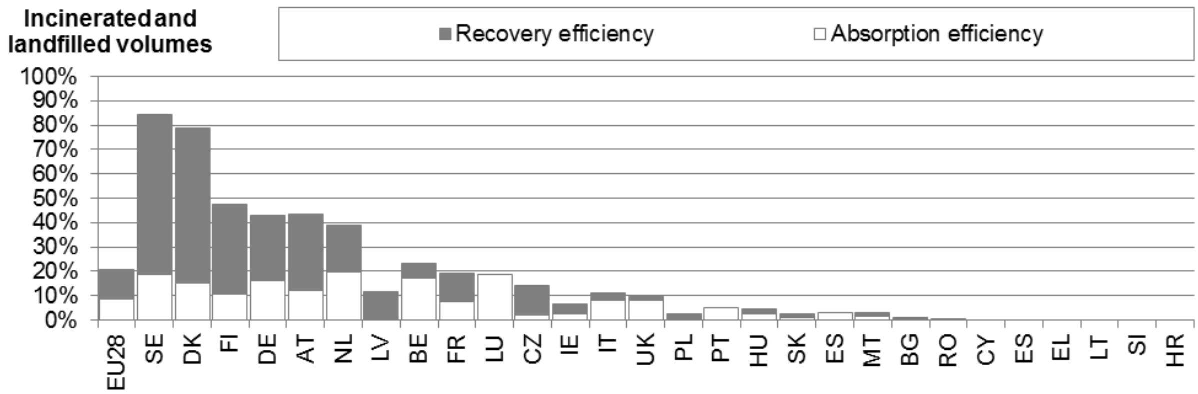

Fig. 5. Distribution of recovery and absorption efficiencies for incinerated and landfilled (non-recycled) volumes of MSW in EU28 Member States during 2012. Sources: [40, 53]. Absorption efficiency is equal to electrical efficiency.

The Eurostat data [40] used in Fig. 5 corresponded to 58.1 Mt (incineration) and 80.7 Mt (landfilling) in 2012, hence totalling at 139 Mt in this year. At the used study conversion factor of 10 GJ/t, this would then correspond to energy magnitudes of approximately 0.58 EJ and 0.81 EJ, respectively, revealing a total 1.39 EJ of energy embedded in these waste fractions. After cross-referencing with IEA data for the same year [53], the total energy content was eventually corrected to 1.51 EJ. By reference to this total volume, the 0.13 EJ of generated electricity rendered an absorption efficiency of 9% and the total heat output of 0.19 EJ (sum of reported heat output from energy sector activities (0.17 EJ) and additional MSW heat output in total final consumption outside the industry sector (0.02 EJ)) rendered an average

EU28 heat recovery efficiency of 12%. From this, an average overall conversion efficiency of only 21% from European MSW fractions currently not recycled or composted indicates that 79% (1.19 EJ) of the total energy content remained unharvested during this year. Thus, it is fair to conclude that more energy can be recovered from current EU MSW not recycled, mainly by redirection of current landfill volumes, and that installation of more incineration capacity, as well as retrofitting of existing units, seems generally viable.

Another decisive aspect to consider in this respect, perhaps also representing a third independent process to monitor, concerns the geographical distribution of current incineration capacities, which by use of pilot project Eurostat data on NUTS2 level is visualised in Fig. 6 [56, 58]. Concerning installed R1 capacity (which notably is summed up to a staggering 149.6 Mt in this dataset, not commented further here) this map illustrates the current distribution of recovery capacity in Europe by normalisation to regional population counts and referring to an anticipated EU28 average ratio (0.3 by relating to the abovementioned total capacity). Since, in practice, a more even distribution of R1 capacities is achievable mainly by increased access to local heat distribution infrastructures, this image indeed underlines the need to expand European district heating if to obtain spatially coherent heat recoveries from present and future WTE conversions.

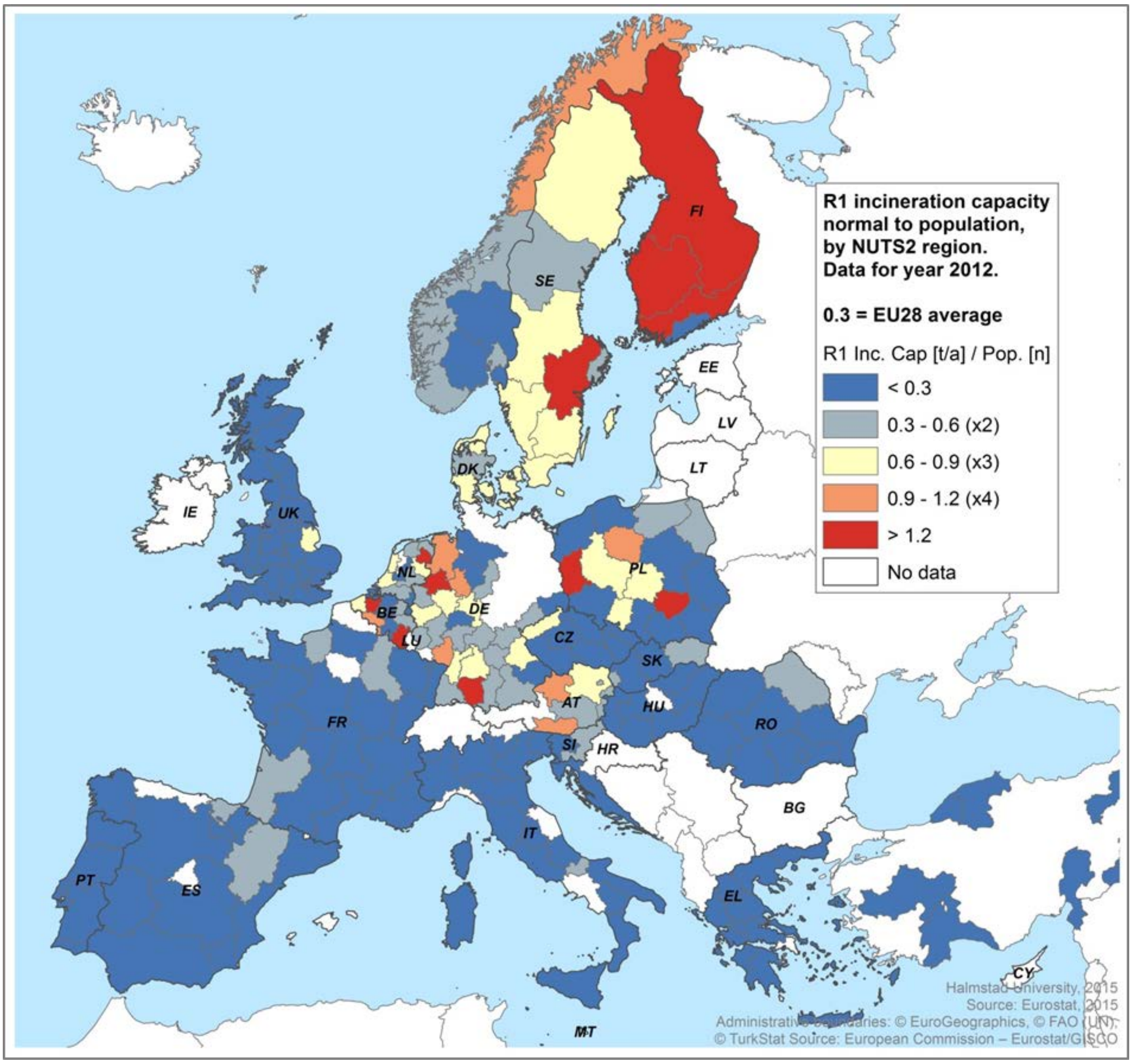

Fig. 6. R1 incineration capacity per NUTS2 region, normal to population. Average EU28 value established as ratio of reported total R1 capacity (149.6 Mt) and total EU28 population in 2012. Sources: [56, 58].

Additionally, contextual developmental trends such as demographically expressed in migrations and urbanisation, do in themselves influence future European waste management conditions. According to used study data, including time series of regional population counts from 1990 to 2014 [56], clear indications of population movements mainly from former east-European MS westward, and as well continued urbanisation processes in practically all large urban zones, should constitute useful information in the construction of future European waste management structures. It is noteworthy, since urban areas represents most beneficial conditions for cost-effective heat distribution [31], while also hosting a majority of energy and industry sector excess heat [36], that Mazzanti and Bozoli [98] found evidence of increased costs for recycling infrastructures (sorting, separation) in city areas compared to rural areas, hereby imposing relatively stronger economic constraints on urban recycling. Finally, illustrative of the many approaches and preferences plausible, current waste imports and exports may reversely be viewed as a potent means by which to achieve a faster reduction of current landfill volumes, as discussed amongst others in [109], which may serve here as a final example of the general complexity characterising European waste management.

5 Conclusions

To conclude, in this paper a literature and data review has been presented by which to answer three initial research questions concerning current and future prospects for heat recovery from waste in European district heating systems. The study has focused on MSW in the EU context with the purpose to identify aggregated general tendencies and trends by which to assess plausible future developments for EU waste generation and management. The main and overarching conclusion is that efficient, i.e. recovery classed WTE conversions (as defined by the R1 formula), in principal requires access to heat distribution infrastructures by which to utilise recovered excess heat. In this respect, current and future deployment levels of district heating systems throughout the European continent are and will be directly reflected in the geographical distribution and spatial spread of efficient waste incineration capacity. For obvious reasons, therefore, EU waste management policies should align and interact to a considerable degree with corresponding energy system related regulations and concerns.

As for the first dedicated research question, historical trends of MSW generation and management among EU MS from 1995 to 2012 reveal, on average, clear evidence of markedly reduced annual volumes designated for landfilling, effectively reflected in increasing corresponding shares for recovery incineration, recycling, and composting, respectively. On MS level, however, landfilling is still excessive in some instances and one third of all generated MSW in Europe is still deposited to land. Apart from representing a valuable source of energy not exploited, this practise is associated with greenhouse gas emissions and stress on local ecosystems. It is further observable, that MS which have successfully implemented waste management routines including all non-landfilling option, i.e. recycling, composting, and recovery incineration, also have lowest landfilling volumes. Additionally, WTE incineration with heat recovery has increased three-fold during the considered period in terms of energy volumes, but recovery capacity is poorly distributed over the European continent.

For the second research question, the study answer is that several different models and approaches have been developed and used in recent years to assess future EU MSW generation and, to a lesser extent, to estimate future deployment levels of European district heating. Originating principally in classical economics, be they characterised by material balances (input/output), multi-sectoral equilibrium models, or statistical econometric approaches, four up-to-date MSW model predictions targeting the EU were selected during the review process. While data leading up to 2012 indicate continuously reduced total MSW generation volumes in Europe, as to which the influence of the financial crisis in 2008 – or perhaps a genuine behavioural shift in consumption patterns – is too early to determine statistically, all considered models predict increased MSW generation volumes for the years to come. The most recent of these, the EU Ref. model, being the only one extending to 2030, foresees a total MSW generation volume of 308 Mt by this year, which, by a historical average ratio between generation and treatment volumes, should correspond to some 294 Mt available for waste management options. Through the availability of regional waste data in later years, future modelling approaches should benefit from applications such as geographically weighted regression analysis and other contemporary Geographical Information Systems (GIS) applications.

Thirdly, based upon the most ambitious and stringent of five scenarios for 2030 elaborated in the context of the EU Ref. model, stipulating 70% recycling and a 5% landfill limit by this year, the study results suggest that the remaining one-quarter could be conceived as available for energy recovery. The key conclusion in this respect, however, is not what exact magnitudes of MSW that will be available for thermal energy conversion in a given year, but rather at what heat recovery efficiencies that available waste volumes will be harnessed in forthcoming WTE conversions. Depending thus, in a deeper sense, on the transitional progress towards more efficient supply structures on future European heat markets (key features in smart energy systems), the presence of local heat distribution infrastructures, as conceived here, is an equally determinant factor as that of total generation volumes regarding prospects for future heat recoveries from waste.

Hereby, district heating systems represent an important infrastructural technology, essential for not only providing energy and environmentally efficient heat supplies to residential, service, and industry sectors, but also for facilitating increased total conversion efficiencies of WTE plants. In such contexts, energy recovery from waste, itself then a driver for future district heating deployment in Europe, represents an enabling technology whereby to achieve improved energy system efficiency while simultaneously reducing the demand for landfilling and deposits, again reminding us of the synergetic opportunities inherent to WTE system technologies.

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