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The conundrum of combustible clean energy: Sweden's history of siting district heating smokestacks in residential areas

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ABSTRACT

Communities may wish to source their energy locally to improve resilience in volatile energy markets, reduce greenhouse gas emissions, and support regional economies. Biomass and waste incineration offer one method that has been broadly adopted in European and Asian countries, particularly in combination with district heating systems. Yet, combustion and the placement of affiliated smokestacks often pose contentious planning obstacles for local communities. Learning from Sweden's example, this research maps where smokestacks are placed in relation to land uses, finding that residential areas comprise nearly 20% of the surrounding land uses within a quarter mile of district-heating associated smokestacks. The research concludes with policy-oriented recommendations for planning district heating.

1. Background: community heat and power

There are several reasons for localizing energy production including diversifying fuel sources for economic resilience (Kohl, 2008), reducing greenhouse gas (GHG) emissions (Lovins and Lovins, 1983; Li, 2005), and stimulating regional economies through new technology development and resource harvesting (Wei et al., 2010; Barrett et al., 2002; Lehtonen and Okkonen, 2013; Yi, 2014). More broadly, there are concerns over dwindling energy supplies, growing energy demands, limitations of fossil fuels, and threats from disruptive climate and political changes. Sudden oil price increases are linked to inflation, rising unemployment, higher interest rates and, as a consequence, high costs to society (Kohl, 2008). A move to local and renewable energy resources is expected to overcome such energy security challenges. In this respect, Kammen et al. (2006) reports that transitioning to a 20% national renewable energy portfolio by 2020 consisting of 85% biomass, 14% wind energy, 1% solar PV would create a total employment of 163,669 for the United States. Proponents are quick to point out that the US solar energy sector already employs more than the oil, natural gas and coal industries combined (DOE, 2017). Bioenergy, the main focus of this research, is currently the largest source of renewable energy and includes biomass and waste incineration, often dubbed "energy recovery" or Waste-to-Energy (WtE).

Indeed, the above reasons prompted many countries to sign the Kyoto Protocol in 1992. Even without the support of a national policy, cities and the state of California are following suit by adopting Climate Action Plans (Wheeler, 2008; Bassett and Shandas, 2010). As communities set goals, they may wish to look to examples of other large-scale successes.

Sweden provides an example of a country which has reduced GHG emissions per capita while re-localizing energy supply and growing the economy. Sweden became one of 32 countries to agree to cap their emissions as part of the United Nations Framework Convention on Climate Change (UNFCCC). Of these countries, twenty-three have been able to reduce their emissions in comparison with the base year of 1990 (UNFCCC, 2011), and Sweden is one of only nine countries that has achieved this reduction while steadily growing its economy (Brinkley, 2014). Sweden also stands out with the earliest and most dramatic GHG reductions (Brinkley, 2014). Carbon dioxide (CO_2) emissions alone fell by 60% since 1970. Until the late 1970s, Sweden sourced over 75% of its energy from imported oil. Today, biomass accounts for 23% of Sweden's energy supply at 129 TW h as compared to 189 TW h (34%) from nuclear fuel, the now dominant energy source (IEA, 2014; SEA, 2015). Through a combination of municipal and national-level policies, transformation of Sweden's energy sector spurred synergistic emissions reductions across waste, agriculture and the built environment (Brinkley, 2014). Though few countries consume more energy per capita than Sweden, the average Swede releases only 4.25 t of carbon dioxide per year into the atmosphere, compared with the EU average of 6.91 t and the US average of 16.15 t (IEA, 2014).

It is broadly acknowledged that Sweden achieved the above by establishing and expanding District Heating (DH) (UNCCC, 2013; Di Lucia and Ericsson, 2014; Werner, 2017). In DH, heat is produced centrally by water heated in a boiler and distributed through underground insulated pipes to heat exchangers at the point of use (Bouffaron and Koch, 2014). DH supplies both hot water and ambient heat. Over half of the

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Fig. 1. Top: Image of Göteborg Energi DH plant in the city center next to a popular pedestrian thoroughfare, apartment buildings, and high-end restaurants. Below: Image of DH plant and DH smokestacks on Stockholm skyline.

energy demand for buildings in the residential and service sectors in Sweden, as well as the United States, goes to heating space and water (SEA, 2015; EIA, 2015). Instead of every home and office operating an individual boiler, nearly 90% of apartment buildings and 17% of single family homes in Sweden are currently heated with DH (Di Lucia and Ericsson, 2014).

DH allowed Sweden to diversify its fuel mixture over a 40 year timespan by converting from traditional oil-fueled boilers to lower-emitting heat sources (Summerton, 1992; Palm, 2006; Magnusson, 2011; UNFCCC, 2013; Di Lucia and Ericsson, 2014; Werner, 2017). DH networks can be coupled with a variety of heat sources, such as heat generated as a byproduct from manufacturing, geothermal, biomass boilers, waste incineration, or combined-heat-and-power (CHP) plants to generate electricity, also called cogeneration (Lund et al., 2014). DH systems also allow for low-cost heat storage for during times of over-production from more volatile renewable energy sources, such as wind and solar (Lund, 2005; Connolly et al., 2014). The versatility of DH allowed Sweden's energy transformation to occur more rapidly than it might have occurred had Sweden needed to retrofit a mobile fleet or fuel sources for boilers in many individual buildings. Now, biofuels provide 40% of the fuel used in DH (Svensk Fjarrvarme, 2016).

For the above reasons, this research focuses on Sweden's DH systems, though such systems are broadly in use worldwide. DH systems are common in European countries such as Finland, Germany, Denmark, the Baltic countries and Eastern Europe (Euroheat and Power, 2007; UNEP, 2013) as well as in Russia and China (Werner, 2004). Because of their efficiency, the United Nations estimates that transition to DH systems, combined with energy efficiency measures, could result in a 30–50% reduction in primary energy consumption, thereby reducing CO_2 emissions by 58% in the energy sector by 2050 and allowing global temperature rises to stay within 2–3 °C (UNEP, 2013)

Yet, using biomass for energy most often means combustion- and requires a smokestack to be sited. Even oil-fueled boilers have affiliated smokestacks. Because heat loss occurs with longer pipelines, DH networks are more efficient when heat production and delivery points are proximate. As a result, incineration facilities and smokestacks are often located near the residential and commercial areas that make use of them. As communities localize energy infrastructure, they will need to consider where to place such facilities.

Many communities are squeamish about siting energy infrastructure in their neighborhood, particularly smokestacks, which have been previously associated with the release of particulate matter, resulting in asthma and other poor health outcomes for nearby communities (Lougheed, 2014). Davis and Henderson (2011) chart the changing American attitude to smokestacks from thinking of them as symbols of American progress during the industrial revolution to locally-unwanted land uses (LULUs) which prompt a Not-In-My-BackYard (NIMBY) response (Stradling and Thorsheim, 1999; Stradling, 1999). Similar complaints are often lodged against wind power and other renewable energies for disrupting viewsheds (Barry et al., 2008; Hirsh and Sovacool, 2013). In addition, there is a long history of siting waste and energy infrastructure in predominantly low-income and minority communities, resulting in health disparities and environmental burdens (Bullard, 2000).

While some European facilities hide the smokestacks behind treelines, there is a counter-history of celebrated architectural design of incineration facilities which seeks to destigmatize the practice, particularly where it is connected to garbage incineration in urban areas. Renowned Viennese architect Friedrich Hundertwasser (1928–2000) designed the Spittelau waste incineration plant in 1989 at the behest of the then-mayor in a bid to keep the plant centrally located. The Spittelau is replete with eye-catching joyful, irregular colors and has become a striking landmark of the Viennese cityscape (Vesilind et al., 2010). Similarly, Copenhagen's Amager Bakke waste incineration plant came online in 2017, and is visible from Copenhagen's iconic Little Mermaid statue in the harbor. The plant is designed to look like ski slope with into the plant's operations to encourage public engagement (Poirier, 2012; Brown, 2014). Sweden has similar examples of DH facilities that feature prominently in city skylines (Fig. 1).

As communities consider incineration options for waste and biofuel, they may wish to learn from the Swedish example of where such infrastructure placed on the landscape. This research is the first effort to explore Sweden's energy transformation spatially. There has yet to be a comparative study for *any* energy industry in relation to surrounding land-uses. This study assembled the first national-level database of DH-affiliated smokestacks, and uses this database to assess the placement of nearly 300 DH affiliated smokestacks in an effort to understand siting decisions. The paper concludes with recommendations for communities seeking to re-localize their energy and heating supply.

2. Methods

Because there is no database of DH smokestacks in Sweden, Data for DH networks was gathered through listings from Swedish District Heating Association, which lists 140 companies and represents over 98% of the delivered DH in Sweden (Svensk Fjarrvarme, 2016). Visual confirmation of smokestacks was gathered through google streetview. This enabled the author to ascertain any aberrant design features, such as those that characterize Vienna's Spittelau; none were identified. This method resulted in 298 observations encompassing central boilers as well as reserve boilers. This figure is an underestimate of smokestacks as many are located behind treelines or in more rural areas where google streetview does not penetrate.

Coordinates of each smokestack were over-layed onto Sweden's 2006 corine land use cover vector data provided by the European Environmental Agency (resolution of 100 × 100 m). Quarter mile buffers were drawn around each data point. Surrounding land uses in polygons were coded as follows:

a. Forest: deciduous forest, coniferous forests, grass lands,
b. Agriculture: arable land, fruit and berries, pastures,
c. Residential: dense urban structures, places with more than 200 inhabitants, places with less than 200 inhabitants,
d. Waterways: ocean, lakes, streams, ponds, lagoons, estuaries,
e. Industrial: industrial areas,
f. Urban Green Space,
g. Other: gravel quarries, mineral extraction sites, rocks, glaciers and permanent snow fields, wetlands,
h. Urban Infrastructure: county buildings, roads, port areas, landfills, construction sites,
i. Recreational: sports halls, shooting ranges, horse facilities, ski slopes, golf course, camping areas, beaches and dunes,
j. Commercial: commercial districts.

The resulting land use profile, subdivided by quarter-mile buffers, was ground-truthed through semi-structured, IRB-approved, hour-long interviews with eleven Swedish district heating experts, including representatives from academia, industry, non-profit and the government (Table 1). Industry experts were asked to comment on smokestack siting procedures and public perception.

3. Findings and discussion

3.1. National context: policies and financing

Sweden's district heating development offers important lessons in energy and heating infrastructure siting. Interviewees indicate that while economics drove the initial adoption and expansion of district heating networks, national financing, municipally driven energy planning, and growing popular environmental support played key roles in continued DH development.

In 1965, Sweden initiated the Million Homes project, and municipalities built large apartment complexes to solve the affordable housing crisis. As part of this public housing construction, the national government offered incentives to construct oil-based DH networks. After WWII, more electricity was needed. In response, municipalities built CHP plants, like that in Göteborg, coupling them into district heating networks. Simultaneously, the national energy company, Vattenfall, offered low electricity prices as large-scale hydroelectric and nuclear power plants came online. The national government no longer pushed for regional energy localization, but municipalities continues to adopt and expand DH nonetheless, despite and sometimes because of changes in electricity pricing (interview confirmed). Where prices were high, DH turned to CHP to produce energy; where electricity prices were low, DH used electricity to generate heat.

In the aftermath of 1973's volatile oil prices tripled the cost of fuel (Wickman, 1988). In response, Sweden formed its 1975 national energy policy on the basis of national security (Swedish Government, 1975). The main objective of the newly launched energy research plan was to move the country from nearly exclusive dependence on imported oil to both improved energy conservation (Kaijser, 2001) and use of more local resources for heat and electricity generation (Haegermark, 2001; SOU, 2007), such as Sweden's abundant forests. Confirmation that the national energy policy was urgent occurred during the second oil crisis in 1978–79, which led to a doubling of the already high oil prices (Wickman, 1988). Subsequently, municipalities focused on growing DH networks by both establishing new networks and building from those originally seeded in the 1970s (interview confirmed).

DH expansion continues to be driven by economic concerns though the push to expand DH markets has shifted from the national government to municipalities and private energy companies. DH currently supplies nearly one-third of heat for residential and services sector compared to just one-twentieth in the 1970s (SEA, 2015). Unlike the pre-war era where the national and municipal government was heavily involved in establishing DH, subsequent expansion and seeding of new DH networks in the 1970s occurred primarily through municipalities, and later in the 1990s through public-private partnerships between district heating companies and municipalities (Frederiksen and Werner, 2013, p 596). For example, Nynäshamn's DH was initiated in 2004 by both the municipality and Fortum (later Värmevärden), a private energy company which operates the CHP and oversees the network. Indeed, economics in both the macro and micro-scale continues to play a large role in growing DH usership. Over 90% of district heating customers in both apartments ($n = 226$) and single family homes ($n = 250$) are satisfied with district heating (Mårtensson, 1998). Economic control over heat supply was the most important rational for joining a district heating system along with having a low-maintenance heating system (Mårtensson, 1998).

Over the course of this same time-period, Swedish planning has increasingly moved from centralized top-down to participatory planning with community engagement beginning in the 1970s (Bjarnadóttir, 2001; Isaksson et al., 2009). The Planning and Building Act and Natural Resources Legislation of 1987 added public participation into the siting process. Yet, while public participation is a valued cornerstone in today's Swedish planning, many contemporary studies have documented the uneven deployment of its use (Soneryd, 2002; Isaksson et al., 2009). For example, Khan (2003) has shown that in

Table 1
Interviewees and affiliated representation. Many interviewees, because of their long careers in district heating, were able to offer a variety of viewpoints from academic, government, non-profit and industry affiliations. For example, Svensk Fjärrvärme (Swedish District Heating Association) is a professional association made of public and private companies that engage in district heating. Similarly, Bengt Göran Dalman previously was chief director of the municipal energy company, Göteborg Energi, and is the former director of Lantmännen Agrovärme and a private consulting firm.

Interviewee	Association	Government	Industry	Non-profit	Academia
Lina Enskog Broman	Swedish District Heating Association	x	x	x	
Patrik Holmström	Swedish District Heating Association	x	x	x	
Raziyeh Khodayari	Swedish District Heating Association	x	x	x	
Bengt Göran Dalman	Lantmännen Agrovärme	x	x		
Bengt Fransman	Habo Energi	x			
Kennet Svedlund	Habo Energi	x			
Anders Gustafsson	Chief engineer of Värmevärden AB in Nynäshamn		x		
Magnus Johansson	Chief director of Luleå Energi AB		x		
Bo Schönbeck	Chief engineer of Ljungby Energi AB	x			
Sven Werner	Professor of Energy Technology at the School of Business, Engineering and Science, Halmstad University				x
Kjell Anderson	Swedish Bioenergy Association			x	

municipalities where public officials oppose wind infrastructure, they often craft extensive public review processes which effectively halt development. In this way, public participation does not neatly correlate with infrastructure siting, public perception or desired community outcomes. While Kahn's study focused on wind energy, it should be noted that district heating is more prevalent than wind and exists in all but four of the 290 municipalities. Because of such messy inconsistencies in the planning process across municipalities, interviews focused on the perceptions of industry representatives and engineers during the siting process. Five of the interviewees are plant managers, engineers who were heavily involved in site selection, fuel source selection, planning, fuel delivery logistics and routing, and communication with the public. Plant managers could speak to public input process with background knowledge of the industry, other plant locations, engineering concerns, and real risks (in comparison to perceived risks).

While DH solved an immediate financial concern for municipalities, interviewees broadly recognized that from an early, if not immediate stage, Swedes saw district heating as a local environmental gain (Mårtensson, 1998; Frederiksen and Werner, 2013, p. 261–269). For example, Bengt Göran Dalman, former director of Göteborg Energi, noted that in Göteborg, Sweden, DH production doubled between 1973 and 2010, while CO_2 emissions fell by half and the city's nitrogen oxide and sulphur dioxide emissions declined even more sharply (also reported in UNEP, 2014). “Cities looked better without the smog” from individual boilers, noted Lina Enskog Broman of the Swedish District Heating Association. Kjell Anderson, a representative from the non-profit Swedish Bioenergy Association echoed this sentiment, noting, “people know that the heat plant smoke stack has replaced hundreds or thousands of individual chimneys, with much more emissions”. This perception of district heating as environmentally beneficial at a local level continues to play a role in community support during the public comment section of the siting and permitting process, as noted by both Ljungby's Municipal Solid Waste (MSW) plant manager as well as Anders Gustafsson, who presided over the most recent large-scale district heating adoption in Nynäshamn.

3.2. What do Swedes think of smokestacks?

The siting of smokestacks was not always met with the same positive perception that DH received overall. The broad Swedish adoption of DH meant siting large-scale smokestacks throughout cities and towns. Interviewees were divided on the cultural perceptions of smokestacks, and answers ranged from entirely positive perceptions to answers qualified by visual aesthetics and public trust. Kjell Andersson, a leading district heating scholar succinctly summarized the Swedish zeitgeist, asserting that “smokestacks [are] not an issue in Sweden. … Most people also know that the smoke coming out of a biomass smokestack is almost only water vapor. Flue gas cleaning is very good today, and this is never an issue with the local communities or the environmental groups. There have been a few exceptions, mainly for plants using waste, or biogas plants, where people fear odor”. Similarly, Anders Gustafsson, chief director of Nynäshamn's CHP relates that people understand that the smokestacks directly benefit them by deriving heat, but that does not always preclude them from feeling nervous about point source emissions. Magnus Johansson, Chief operator of Luleå’s CHP agreed that “the community is very supportive”, but that they hold the facilities to high environmental standards and expect operations to be safe and environmentally sound.

Support for DH and distaste for living near a smokestack are not mutually exclusive. As Bo Schönbeck, chief operator of Ljungby's waste-to-energy CHP plant notes, heat bills are some of the lowest in Sweden since their municipally-owned DH plant came online. This allows the municipality to lure new businesses to the town because of lower utility prices. Schönbeck stated that while the community is supportive and nearly the entire town has come for a tour of the plant, “even if you know that the smoke is not dangerous or poisonous, people still don’t want to see it”. Similarly, Bengt Fransson, chief operator of Habo Energi noted that, “Even if you don’t burn anything, people don’t want to live near one”. Bengt Göran Dalman, with over 40 years’ experience operating Göteborg's DH notes that the waste incinerator in Göteborg would have never been allowed to be placed where it is, close to hotels and the center city (Fig. 1). “You will always get complaints from the neighbors”, he said. Indeed, three plants noted that the wind directionality guided plant location for purely visual purposes so that townspeople would not need to see the vapors from the smokestack.

To this end, Professor Sven Werner, an academic who has studied district heating for the past 35 years notes that Swedes do not really know about DH, and might not even recognize a smokestack as such. Despite the prevalence of DH, only 44% of Swedes spontaneously mentioned DH as a heat source in a 2014 survey ($n = 1050$, Värmerapporten, 2015) indicating that the technology is not at the forefront of public thought or opinion. As the above interviews would suggest, careful attention to siting in order to decrease visibility of both smokestacks and smoke may help in keeping this prevalent heat source out of public thought with the result that Swedes may not think much at all about the many smokestacks that dot the skyline of every major city (see Fig. 1).

3.3. Siting decision-making

Interview results indicate that historical plant locations dictated the growth and expansion of new facilities. Plants were originally seeded through public housing programs, such as the 1960's Million Homes Project. For example, Bengt Fransson, the chief of Habo energy

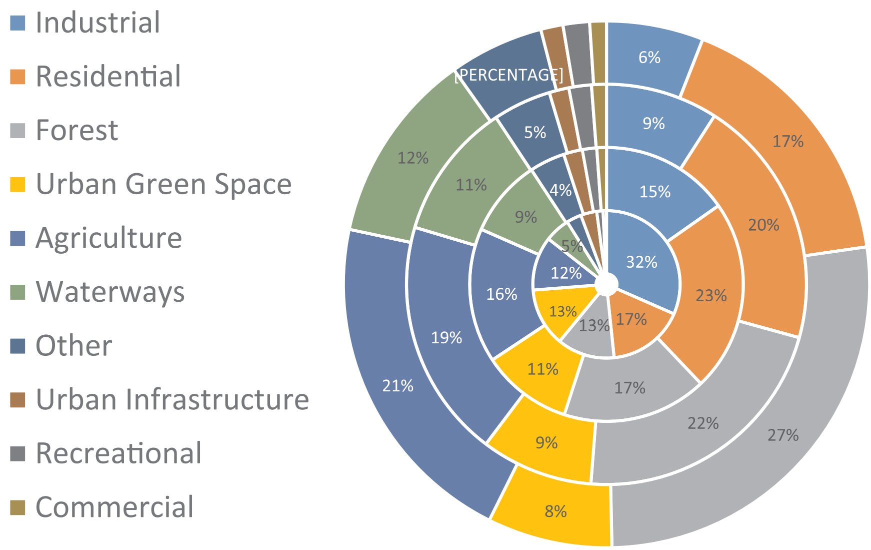

Fig. 2. Land use profile within quarter mile buffers of district heating-associated smokestack.

indicates that the new biomass plant built in the mid-1990s was placed so that it could couple into the existing district heating networks, originally established in the 1970s. As a result, the biomass plant is located in a residential area. In all cases, original networks were gradually expanded with new reserve boilers and updated to renewable fuel sources through changing boiler types.

All interviewees noted that it is best to site new plants in industrial, agricultural or greenfield sites outside of the city. DH plants with more distant locations from the residential areas they supply need to offset the cost of longer pipes and insulation with facility design, lower cost of land, and permitting. To this end, larger plants can be placed further away from the customers they serve precisely because they generate more heat.

However, interviews indicate that facility design and orientation to residential land uses may matter more to siting than facility size or fuel-type. As the google earth images and interviews verified, Sweden does not have such architecturally celebrated cases of DH plant design. It is not uncommon, however, for architectural involvement in facility design. Bo Schönbeck of Ljungby Energy notes, their waste-to-energy facility processes municipal waste, and the aesthetics of the plant along with its inversion air techniques are vital to prevent smells from escaping and troubling the nearby residential areas. Managers also pay special attention to maintaining the grounds around the plant to promote a sense of “cleanliness and organization”.

Reserve boilers are inevitably and predominately located in residential areas. Reserve boilers are rarely turned on, and therefore rarely emit smoke. Anders Gustafsson, chief director of Nynäshamn's CHP, relates that reserve boilers receive very few complaints because the people who live nearest them have the most use for them and understand why the infrastructure is there. On the other hand, he noted that people who live near the smokestacks may still be nervous about emissions. In the case of Nynäshamn, a smaller oil and biomass boiler is located in a residential area and receives more complaints than the larger power station which processes waste and produces more than twenty-times the power. The larger facility is located further away from residential areas and within industrial area. Similarly, in the case of Habo, where the biomass plant is located in a residential area, the managers aim to move its location in a few years.

Because Sweden has developed DH networks and associated smokestacks since the 1940s, the land uses surrounding many plants have dramatically changed. For example, Stockholm (Fortum) just inaugurated the world's largest biomass CHP, located at Värtan harbor close to inner city Stockholm. All the biomass will be transported into the city by train and boat, entering the plant through underground tunnels. The location of this plant, and many other new plants, are built on the sites of older heat plants. When this site the Stockholm site first developed, it was not surrounded by residential land uses. Residential and commercial office buildings slowly grew up around the site of the plant. This finding suggests the tenacious hold of DH infrastructure on its historic site, despite changes to surrounding land use profiles. Göteborg, Sweden's second largest city, has a similar situation with its waste incineration plant, located near the center city. All interviewees agreed that such centrally located plants can only occur if they are grandfathered into place and would rarely be granted such a central location if they were not grandfathered. Professor Sven Werner adds that at least in the case of Vienna, Austria the then mayor fought to have the waste incineration plant grandfathered into its central location to prove that there was nothing harmful about the emissions. According to such logic, to relocate DH boilers outside the city and hide them would be equivalent to saying they are dangerous.

3.4. Land use: where did they put all the smokestacks?

The largest non-aggregated land use category is industrial areas, comprising 32% of land uses surrounding smokestacks, followed by: urban green spaces (13%), residential areas with more than 200 inhabitants and with greater area of gardens” (10%), arable land (8%) and “places with more than 200 inhabitants, and smaller areas of gardens/green” (7%). When residential land uses are aggregated, smokestacks are most predominantly located near industrial land uses (32%), followed by residential (17%), and agricultural (13%) land uses. Residential land uses are the second largest land use in proximity to district heating affiliated smokestacks, and the largest land use from 0.25 to 0.5 miles from the smokestacks (Fig. 2).

DH plants had a mixture of fuel sources. Of the 154 plants that reported fuel mixtures, the majority drew from woody biomass (75%), waste heat from industry (30%), and MSW (12%), with other heat sources that included heat from treated sewage (3%), heat pumps (3%), landfill gas (3%) and solar (3%). Sourcing is representative of the national DH fuel use averages where wood fuels make up the majority of fuel supply followed by MSW and waste heat (Olsson et al., 2016; Werner, 2017). Nearly all plants report using some oil or natural gas during peak heat demand in the winter months. Because of various fuel mixtures within each network and coupling with industry, plants could not be easily stratified based on fuel-type. For example, one plant drew mainly from woody biomass, but also used landfill gas and residual heat

Table 2
Residential land use within a quarter mile of district heating smokestack, based off of 108 data points. When controlling for plants that handle MSW and are coupled with industry, total data points are 45 entries.

Time period when DH plant was established	1940–1980	1980–2000	> 2000
% residential land within 0.25 mi	11	23	23
% residential land for non- waste and industry coupled plants	24	26	22

from a small coffee roasting operation.

The importance to facility siting near both end-users and land-uses associated with fuel sources is evident and unsurprising, but nonetheless provides novel empiric evidence for later feasibility models that consider site suitability. Co-location of facilities with agricultural, industrial and forest land uses puts plants in proximity to readily available fuel sources in crop byproduct, waste heat and forest byproducts respectively. While plants source from a global market, interviewees noted that the proximity of supplemental local sources played a key role in reducing transportation costs for fuel. For example, Skara's boiler burns hay. Before the plant was built, farmers would clear their fields by burning the hay on the field, releasing soot into the air (interview confirmed). Now, farmers transport the hay to the biomass boiler. Many facilities offer agricultural waste disposal for slaughterhouses or crop residues, which are incinerated and converted to heat. Similarly, many plants with CHP supply energy to industries and use resulting heat from industries. Industrial waste heat was often previously discharged into waterways, explaining the prevalence of nearby water land uses partially through industry coupling. The dominance of nearby residential land uses is explained by the dominance of the housing sector as district heating users.

Interviewees indicated that older plants would be more predominantly surrounded by residential land uses as surrounding land uses converted previous greenfield and industrial sites to residential and commercial uses. This conception was not born out in the mapping where smokestacks from plants established prior to 1980 were surrounded by just 11% residential land uses, compared to 23% in for plants established in later years (Table 2). Surprisingly, for plants built after 2010, nearly one-third of surrounding land uses are residential (Table 2). Interviewees largely indicated that newer plants were more consistently located on the outskirts of towns and were less likely to be located next to residential land uses, but data did not corroborate this assumption. An alternate explanation may be that newer plants locate more frequently near single-family homes on the edge of town, still within residential land uses but less frequently in city centers. Another explanation may be that attitudes to smokestacks has slowly shifted over the years, making it easier for land use planners to site facilities near end-users without protest. There is evidence from other energy literatures that proximity to energy infrastructure changes public perception to support it. For example, in a survey of 2701 residents, those who live closer to nuclear power plants are more likely to prefer that energy source and expansion of it (Greenberg, 2009).

Yet another explanation could be that older plants are less appealing, aesthetically or otherwise, and residential areas were not as likely to spring up around them as interviewees suggested. Newer plants could also be grandfathered into older, centrally-located industrial or DH sites. Indeed, fourteen percent of plants are reported to be grandfathered into a previous energy supply site, and have, on average, 32% of the surrounding land within a quarter mile radius in residential uses.

The stratification of primary fuel type and location shows that biomass plants are most likely to be located near residential areas, in comparison to DH reliant on MSW and industrial waste heat. Over half the plants that source MSW were established prior to 1980, and have on average only 8% of the land within a quarter mile radius in residential uses, compared to the dominant land use of industry (32% of surrounding land use within a quarter mile). Similarly, plants coupled to industry waste heat had 52% of the surrounding land within a quarter mile radius in industrial land use (Table 2).

4. Conclusions and policy implications

Sweden's broad adoption of DH allows a 75-year perspective on best practices for facility siting. Over this time period, Sweden quietly, rapidly and unintentionally reduced GHG emissions by expanding DH markets in the name of economics and re-localizing energy supply. While Sweden is not the only country to widely adopt DH, broad acceptance of the technology and national lauding of its success, offer insight for other regions considering similar feats in GHG emissions reductions and corresponding transformation of the energy and heating sectors.

As this research shows, facility siting as early as 1950s continues to exert a legacy impact on future DH development, predicating network growth and siting for new boilers. For cities considering micro-grids, the placement of such investments early on will naturally govern future expansion. Policymakers should be aware of the potential for initial siting decisions to influence future energy infrastructure development not only at the site, but in surrounding neighborhoods as the DH network is expanded in later decades.

To this end, the land-use profile provided in this study offers an empirically-based example for those wishing to model suitable sites for seeding DH networks. As this research shows, it will not be enough to simply model demand on its own. Moreover, because this is the first study of its kind to compare an energy infrastructure with surrounding land-uses, future studies could compare alternative energy industries to see which are a better match for particular land-use profiles. Already, land-use suitability studies are considered for large-scale solar (Hoffacker et al., 2017).

Last, in keeping with overwhelming positive public surveys of DH users, this research shows that DH systems are increasingly sited near residential areas. This finding supports a novel counter-narrative to the history of siting smokestacks near residential areas and gives credence to the general perception that the Swedes have figured out how to create combustible clean energy without generating locally-unwanted land-uses. Interviewees were quick to note that such acceptance may hinge on the low profile that Swedish DH has visually. Siting decisions are aimed largely at limiting the visibility of flue emissions. As one interviewee suggested, it may be less that Swedes accept DH insomuch as they are not aware of it- all due to conscious facility design choices made by plant managers. While Copenhagen's Amager Bakke and Vienna's Spittelau plants draw public attention, the Swedish case of DH emphasizes the importance of unobtrusive design in order to keep energy sited close by.

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