Urban Mining potential in local power grids: Hibernating copper and aluminium in Linköping

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Abstract
Power grids have a high content of metal, mainly copper and aluminium. When old cables reach their end-of-life, or in some way lose their intended purpose, they are usually left lying in their subsurface position. Material no longer used, but not yet discarded as waste, is in a state known as hibernation. Over time there is an accumulation of hibernating cables under ground that potentially could be recovered or “mined”. The aim of this study is to examine the total hibernating metal content of an urban, subsurface power grid, how it is distributed and also what reasons for disconnection are the most common. The focus of the study is the power grid of Linköping. Using a GIS based variant of material flow analysis the hibernating metal stock is examined both in terms of size and spatial distribution. The results of the study show a significant amount of hibernating copper and aluminium; in total 240 tons of metal were identified. By comparing the results with previous studies both similar and differing patterns appear. The main differences lie in the distribution of the stock within the city which is affected by the characteristics of the cities. When examining the reasons for disconnection continuous repair and maintenance work seems to be the most common reason for disconnection of cables. Further studies on how the characteristics of a city affects the formation of hibernating metal stocks in the infrastructure are suggested.

Keywords: GIS, metal stocks, MFA, power grid, urban mining
1 Introduction

The human society's need for metals gives rise to a constant flow of metal resources from the natural environment into the society. This flow comes with numerous implications, such as environmental impact, energy consumption and falling metal concentrations in ore (Norgate and Hauge 2009). This has led to an awareness of, and interest in, resource recovery from alternative sources. The UNEP (2010) has for instance identified the potential in recycling metals located in the built environment. It has been established that the inflow of material to the society is greater than the outflow, there is thus a so called stock of material, or metal, that continuously grows (Brunner 1999; Bergbäck et al. 2001). These material stocks are especially dense in cities, as they need an accumulation of materials to grow and develop (Brunner 2007).

These urban metal stocks could potentially be recovered and recycled, or “mined”, which is studied in urban mining studies. Most parts of these stocks are, however, in active use and could therefore not be removed from their current position without serious implications. A fraction of the anthropogenic metal stocks are though in a state of “hibernation”, in urban mining terms (Kapur and Graedel 2006). The hibernating metal stock consists of various metal products that no longer are in active use but that not yet have been discarded as waste (Kapur and Graedel 2006). These stocks could in theory be recovered.

If this is to be made possible the physical properties of these stocks, and also how these are formed need to be examined and understood, which is studied within urban mining research. Numerous studies have been examining the urban or anthropogenic metal stocks and flows in society on varying levels. There are studies that have quantified stocks and flows to determine their size (Spatari et al. 2005; Klinglmair and Fellner 2010), some other studies have gone further and examined the spatiality of stocks to identify where the stocks are located and how they are distributed (van Beers and Graedel 2003; Recalde et al. 2007). Most studies do however examine the in-use stocks, this since hibernating stocks often are more difficult to assess (Kapur and Graedel 2006).

Infrasystems1 have been identified to contain large amounts of metals, and although they have large amounts of in-use metals they do also have significant amounts of hibernating portions as well (Wendell 2005; Krook et al. 2011; Andersson and Petersson 2011; Wallsten et al. 2012). This is especially true for subsurface infrasystems which, due to their “invisibility” and inaccessible nature, remain in their subsurface position even after being disconnected. Disconnected parts of subsurface infrassystems are thus likely to enter hibernation (Wallsten et al. 2013). These systems include cables and pipes for transmission of energy, water and for communication.

Material flow studies on subsurface infrasystems are not too common, but some recent studies have quantified such infrasystem stocks in urban environments, including the hibernating parts. Wallsten et al. (2012) have quantified the in-use and hibernating stocks for all major, metallic, subsurface infrasystems in an urban area; specifically the city of Norrköping. This study does also examine the spatial distribution of the these stocks. Wallsten et al. (2012) identifies the need for comparative studies in this area; different cities probably have different sizes and composition of their stock depending on their history and characteristics. Similar studies could increase the understanding of the size and composition of these urban metal stocks and also how these stocks are shaped by the differing conditions of cities. If the location of these stock would be known, then that could be the basis for a potential recovery of these resources. There are also studies that have examined the reason for why infrasystem parts are disconnected and left in hibernation (see e.g. Wallsten et al. 2013). By studying how common these mechanisms for disconnection are, measures could

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1 Infrasystem is here defined as a single technical system that together with other infrasystems make up the infrastructure.
possibly be taken to avoid a future accumulation of metal when infrasystems are disconnected.

1.1 Aim
The aim of this thesis is to examine the urban mining potential of metal in the subsurface infrasystems in a city. This includes a quantification of the size of the metal stock and also a determination of the spatial distribution of the stock. The urban area of Linköping city and its subsurface power grid is the focus of this study. The examined metals include copper and aluminium. Further, this study seeks to increase the understanding of how these metal stocks in infrasystems are shaped and how the characteristics of a city affect the size and composition of the metal stock. To put this in a perspective, the metal stock of Linköping is compared to an earlier, similar study conducted in Norrköping.

1.1.1 Research questions
- What is the total size of the hibernating metal stocks in the Linköping power grid, and how is this stock distributed spatially within the city?
- How is this metal stock affected by age and building types of different city districts?
- What differences and similarities could be found in comparison with the hibernating infrasystem stock in Norrköping?
- What are the main reasons for disconnection of cables in Linköping?
2 Background

2.1 Industrial ecology and -metabolism
Industrial ecology is a broad concept and not strictly defined (O'Rourke et al. 1996). Central to industrial ecology research is the flow of resources and material through the human society, or the anthroposphere, and how the use of natural resources could be used more efficiently. This is closely related to the field of industrial metabolism where the industrial society's consumption and processing of natural resources are studied and metaphorically compared to the metabolism of organisms (Ayres 1994). The anthropogenic metabolism of resources has also been compared to natural ecosystems (Frosch 1992).

An important aspect of the anthropogenic resource flows, that is studied within industrial ecology, is the creation of waste or discarded resources. Large portions of the extracted and processed natural resources end up in unknown sinks, or stocks (Brunner 1999), and studies have concluded that for some materials the majority of the used resources are lost somewhere (Mao and Graedel 2009). Previous anthropogenic material flow studies have examined the potential pollution problems caused by flows and accumulation of e.g. heavy metals (Bergbäck et al. 2001; Lindqvist and Eklund 2002). More recent studies have instead examined the potential for resource recovery from these accumulated material stocks, where most often the in-use stocks are measured (see e.g. van Beers and Graedel 2003).

The hibernating stocks, however, have not been studied to any large extent, and its properties and composition remain relatively unexplored (Kapur and Graedel 2006). The fact that natural resources end up and accumulate in stocks of unknown size and location is a proof for an inefficient use of natural resources.

2.2 Hibernating stocks in the subsurface infrasystems in Norrköping
Wallsten et al. (2012) have studied the subsurface infrasystems of Norrköping, including both cables and pipes from various technical systems. The city of Norrköping shares many similar characteristics with Linköping; both being similarly sized, and aged cities in the same geographical region. There are also notable differences between the cities, amongst else concerning their history of industrial development. Even though the hibernating metal stocks in Norrköping are compared to the ones found in Linköping in this thesis, the characteristics of the two cities and their significance for these differences are not.

Wallsten et al. (2012) have identified in total 250 tons of copper and 25 tons of aluminium in the AC power grid (i.e. alternating current, the dominating type of electric power transmission in power grids today). Norrköping does have significant amounts of private cables, as well as an obsolete DC power grid (i.e. direct current, today a mostly obsolete method of power transmission in power grids, largely replaced by AC). Both of these are excluded from the comparison with Linköping. The spatial distribution of this metal stock is shown in appendix 1. The spatial distribution of the metal stock in Norrköping is characterized by a strong centrality; the most metal is found in more central parts of the city, with less metal in the more peripheral areas.

The methodology used by Wallsten et al. (2012) differs notably from the one used in this thesis. Wallsten has conducted a bottom-up analysis (see e.g. Kapur & Graedel 2006) of the metal stocks for only a few limited areas of the city. These quantified areas have then been extrapolated for the rest of the city. The quantified areas have different types of buildings; an are with detached houses, an inner-city area, an industrial area etc. The stock of the quantified industrial area is then extrapolated to all other industrial areas, and so on.
2.3 Mechanisms behind disconnection of infrastructure

The reason behind disconnection of infrasystems, and also why these disconnected parts are left in hibernation, is described by Wallsten et al. (2013). Wallsten et al. divides the mechanisms behind disconnection into three categories metaphorically described as “cellular dormancy”, “paralysis” and “infrastructure coma”. The two former categories describe infrasystems where parts of a still active system that have been disconnected, while the latter category is used to describe complete infrasystems no longer in use.

The differences between these categories lies part in the reason behind disconnection, part in the physical characteristics of the disconnected infrasystem parts. Wallsten et al. (2013) describe dormant cells of infrastructure as isolated and fragmented parts of infrasystems. This could be seen as shorter parts of disconnected cables or pipes spread throughout the urban area. Dormant cells are usually the result of repair and maintenance work on the infrasystems; shorter sections are replaced due to damage or end-of-life.

Infrastructure in paralysis is described by Wallsten et al. (2013) as larger zones where the infrasystems is disconnected. Characteristic for this pattern is longer parts of the infrastructure connected in clusters. Such a disconnection pattern is more often caused by urban renewal programs where e.g. an industrial area is redeveloped into a residential or commercial district. The whole infrasystem of such an area could thus be disconnected virtually at once.
3 Material and methods

In order to examine the power grid, and its metal content, of Linköping a GIS based approach of material flow analysis (MFA) (see e.g. Brunner and Rechberger 2004) was used as described by Wallsten et al. (2012). The method is essentially a so called bottom-up variant of MFA where material stocks are quantified by measuring the stocks directly (Kapur and Graedel 2006). This in contrast to the top-down approach where the size of the stocks are measured indirectly by examining the in and outflows to the stock for a certain period of time. The necessary data was sourced from the power grid operator Utsikt/Tekniska Verken. The whole procedure is described in the following sections.

The used methodology offers a high precision and detail of the studied object compared to other alternative methods. This is why the method has been chosen. This method is, however, not without its drawbacks. Quantifying a material stock using the bottom-up method (Kapur & Graedel 2006) is a very resource intensive procedure. Extensive amounts of time, labor and data are needed. This is partly a reason to why this method has not been used to any large extend in previous studies (Kapur and Graedel 2006). Although this is the reason for the high detail of the methodology, it must be weighed against the possible inclusion of other systems or stocks in the study. Due to the resource requirements of this method, a study using this methodology must be relatively delimited in scope. Wallsten et al. (2012) did for instance use this method with some simplifications but did on the other hand include a multitude of infrasystems in the study. Simplifications could thus be a way to sacrifice detail for an increased scope of a study.

Another important aspect of this method is the needed data material. Large amounts of data are needed in order to reach the full detail of the studied object. The collection and subsequent processing of this data is a key reason for the resource intensiveness of this method. The accessibility of data is also a potential issue, especially when it comes to infrastructure where the data could be sensitive or classified. If not all the needed data could be retrieved then simplifications would be necessary. There could also be situations where the needed data no longer exists or is in a format where it would take unreasonable time and labor to collect it.

For this study though a high level of detail of the studied infrasystem has been desired and simplifications has thus been avoided to as a large extent as possible.

3.1 Material and data collection

In order to determine the size, distribution and composition of the hibernating metal stock a complete map of the Linköping power grid was needed. This was acquired from the grid owner in the form of digital GIS map files, which was divided between low and medium voltage cables. This material was, however, incomplete and had to be complemented using other sources. The digital GIS documentation have been used by the grid owner since approximately 2000 until today, and does mainly cover cables disconnected during this period of time.

Before the digital GIS documentation came into use the grid owner documented all cables, including disconnected ones, using plastic sheet maps. These maps were used from the early 1970’s to the late 1990’s when they were replaced. In order to cover disconnected cables for the period from approximately 1970 until today these maps had to be used and combined with the digital GIS map files. Due to the availability of data, cables disconnected before 1970 is not included in the study.

Since these maps were in a non-digital format they had to be digitalized in order to be used with the preferred GIS based methodology. The maps were retrieved from the grid owner’s archive where they were examined to contain disconnected cables. All map sheets that contained disconnected cables, in total 419 map sheets, were digitalized using scanning.
In addition to cable data, data for describing the city’s characteristics in terms of building types, and age of different city district were needed. A complete GIS map for all buildings in the Linköping urban area was acquired from Linköping municipality. This map contained data regarding building type and building construction year.

3.2 Data processing
When the map sheets had been scanned, GIS maps had to be created. All digital map sheets were imported into GIS software (MapInfo 11.0). Using the GIS software polyline objects were created to represent each disconnected cable, this was done using manual digitalization (i.e. “drawing” line objects on top of the cables on the maps). Each cable object was assigned data for cable type, object length, and metal concentration values for both copper and aluminium (i.e. kg Cu or Al per meter). Each cables object was given the corresponding cable type as documented on the map sheets. For some of the cables the cable type could not be identified and was thus labeled as “unknown”. Cable length was calculated using the GIS software tools and metal concentration values was assigned to each cable object according to EBR (2009) in accordance to their labeled cable type. For cables labeled as “unknown” an average metal concentration value based on the known cable types was used instead.

The procedure of assigning values for length and metal concentration was repeated for the post 1995 GIS maps as well. These cable objects already had labels for cable type and assignment of cable type was thus not needed. An average metal concentration value for these cables of an unknown type was used as well.

All cable map layers were then combined with the map layer for buildings. All parts of cables that were overlapping buildings were cut and removed from the dataset. This since both the status, position and the availability of the cables in or under buildings are unknown.

When these procedures were completed a complete map for the disconnected parts of the Linköping power grid was obtained. However, since data from two different sources had been combined it became apparent that there was an overlap of data between the two sources; cables from the map sheets were also present on the digital GIS maps. The data overlap was confirmed by the grid owner (Nilsson, 2013). The overlap was adjusted by visually inspecting the data, i.e. the cable objects. Overlapping doublets were removed from the GIS dataset.

3.3 Analysis

3.3.1 Calculation of total metal stock and its distribution
With length and metal concentration known for each cable object in the whole city the total metal stock could be calculated by multiplying these values to obtain the specific metal content for each cable. This was done separately for both copper and aluminium.

<table>
<thead>
<tr>
<th>District</th>
<th>SFH</th>
<th>MFH</th>
<th>Ind.</th>
<th>Com.</th>
<th>Spe.</th>
</tr>
</thead>
<tbody>
<tr>
<td>Skågetorp</td>
<td>0</td>
<td>78</td>
<td>1</td>
<td>9</td>
<td>12</td>
</tr>
<tr>
<td>Tomby</td>
<td>0</td>
<td>53</td>
<td>44</td>
<td>2</td>
<td></td>
</tr>
<tr>
<td>Källerslåd</td>
<td>1</td>
<td>58</td>
<td>14</td>
<td>27</td>
<td></td>
</tr>
<tr>
<td>Tallboda</td>
<td>52</td>
<td>29</td>
<td>13</td>
<td>1</td>
<td>6</td>
</tr>
<tr>
<td>Ryd</td>
<td>17</td>
<td>65</td>
<td>5</td>
<td>12</td>
<td></td>
</tr>
<tr>
<td>Gottfridsberg</td>
<td>26</td>
<td>54</td>
<td>10</td>
<td>1</td>
<td>10</td>
</tr>
<tr>
<td>Vasastaden</td>
<td>7</td>
<td>49</td>
<td>29</td>
<td>11</td>
<td>11</td>
</tr>
<tr>
<td>Innerstaden</td>
<td>5</td>
<td>62</td>
<td>0</td>
<td>15</td>
<td>18</td>
</tr>
<tr>
<td>Tantefors</td>
<td>10</td>
<td>14</td>
<td>66</td>
<td>4</td>
<td>7</td>
</tr>
<tr>
<td>Jägavallen</td>
<td>35</td>
<td>0</td>
<td>44</td>
<td>18</td>
<td>3</td>
</tr>
<tr>
<td>Mjärdevi</td>
<td>0</td>
<td>27</td>
<td>66</td>
<td>7</td>
<td></td>
</tr>
<tr>
<td>Västra Valla</td>
<td>0</td>
<td>3</td>
<td>0</td>
<td>1</td>
<td>96</td>
</tr>
<tr>
<td>Östra Valla</td>
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<td>50</td>
<td>1</td>
<td>17</td>
<td>13</td>
</tr>
<tr>
<td>Ekkällen</td>
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<td>24</td>
<td>0</td>
<td>0</td>
<td>72</td>
</tr>
<tr>
<td>Garrisonen</td>
<td>7</td>
<td>23</td>
<td>0</td>
<td>47</td>
<td>23</td>
</tr>
<tr>
<td>Ramshäll</td>
<td>54</td>
<td>39</td>
<td>0</td>
<td>0</td>
<td>7</td>
</tr>
<tr>
<td>Hejdégården</td>
<td>32</td>
<td>62</td>
<td>5</td>
<td>1</td>
<td>0</td>
</tr>
<tr>
<td>Vimanhsll</td>
<td>83</td>
<td>10</td>
<td>1</td>
<td>0</td>
<td>6</td>
</tr>
<tr>
<td>Johanellund</td>
<td>23</td>
<td>58</td>
<td>1</td>
<td>4</td>
<td>15</td>
</tr>
<tr>
<td>Hackefors</td>
<td>32</td>
<td>2</td>
<td>60</td>
<td>1</td>
<td>6</td>
</tr>
<tr>
<td>Lambohov</td>
<td>49</td>
<td>40</td>
<td>2</td>
<td>0</td>
<td>10</td>
</tr>
<tr>
<td>Djurgården</td>
<td>77</td>
<td>0</td>
<td>7</td>
<td>23</td>
<td>0</td>
</tr>
<tr>
<td>Berga</td>
<td>40</td>
<td>49</td>
<td>0</td>
<td>1</td>
<td>10</td>
</tr>
<tr>
<td>Vidingssjö</td>
<td>59</td>
<td>37</td>
<td>0</td>
<td>0</td>
<td>4</td>
</tr>
<tr>
<td>Ekholmen</td>
<td>36</td>
<td>40</td>
<td>0</td>
<td>7</td>
<td>1</td>
</tr>
<tr>
<td>Hjulsbro</td>
<td>76</td>
<td>16</td>
<td>0</td>
<td>1</td>
<td>7</td>
</tr>
<tr>
<td>Ullstämma</td>
<td>59</td>
<td>24</td>
<td>0</td>
<td>2</td>
<td>14</td>
</tr>
</tbody>
</table>

Table 1. Share (in %) of building types of the total building area per city district. Building types: Single-Family Houses, Multi-Family Houses, Industries, Commercial buildings, Special buildings.
In order to examine the distribution of the stock in the city the total copper and aluminium content was calculated for each city district; i.e. the sum of the weight for all cables within the borders of a district. In order to allocate the weight correctly to each district the cable objects were split at the point of intersection with district borders. Both the sum of weights and also the districts’ share of the city's total stock was calculated.

3.3.2 Categorization of city districts into different usage types
The GIS map layer of buildings in Linköping contains information for each building object concerning building type. The building types were aggregated into six different categories; single-family houses, multi-family houses, industrial buildings, retail and commercial buildings, special buildings (including schools, hospitals, public buildings etc.) and other buildings (e.g. garages and complementary buildings). The “other buildings” category was the dominating one for all city districts. These buildings were deemed not to be descriptive for the characteristics of the city districts. This since they are of a “generic” type and are mostly complements to other buildings where the type is more characteristic. Because of this all buildings of this category were removed from the dataset.

In order to determine the dominating building type for each district the total building area (using the polygon object area) for each building category for each city district was calculated. From this the building categories' share of the total building area for each district were calculated. The share of building types for each city district is shown in table 1. This is also visualized in figure 1 where the districts have been categorized according to the building type with the largest share.

![Fig 1. The city districts of Linköping categorized according to the most common building type in per district.](image)

3.3.3 Categorization of city districts into different age intervals
The buildings map did also contain data for the construction year for the buildings. This data was used to categorize the districts into different age categories. In order to do this the average construction year for the buildings in each district was calculated to give rough indication of the age of the districts' building stock. A majority of the buildings did, however, have a missing value for construction year, which probably affected the calculated average value.
In addition to the average construction year, the installation year for different parts of the medium voltage grid in Linköping was used. These two data sources was combined in order to sort the districts into age categories. The categories used are: before 1960, 1960-1979 and after 1979. Two of the districts contained so few buildings with age data that the average age could not be calculated and are thus classified as “no data”. The age for the city districts is illustrated in figure 2.

![Figure 2](image-url)  
*Fig 2. The approximate age of the building stock and power grid of the city districts.*

### 3.3.4 Comparison with Norrköping

In order to put the findings of this study in a perspective the hibernating metal stock of the Linköping power grid was compared to the equivalent stock in Norrköping. Norrköping has been studied by Wallsten et al. (2012) and it is that study that is the basis for the comparison. It must be noted though that the methodologies between this study and the one of Wallsten et al. differ significantly. This study has made use of a bottom-up approach and directly quantified every cable in the city for the studied time period whereas Wallsten et al. only have made a direct quantification of a few parts of the studied city and extrapolated the values. There is a possibility that Wallsten et al. is over- or underestimating the size of the metal stock.

### 3.3.5 Analysis of cables lengths and reasons for disconnection

The disconnection patterns described by Wallsten et al. (2013) are used here as an indicator for why cables have been disconnected. The two patterns used are “dormant cells” and “infrastructure paralysis”. Where the first one describes shorter cables disconnected due to repair and maintenance work, and the latter one describes longer and larger clusters of cables. The length parameter of the cable objects are thus used as an indicator for disconnection
reason. The actual reason for disconnection, however, cannot be assessed with this quantitative method. Although it is deemed as a way to see which disconnection patterns that is more common than the other. Also, it is not possible to assign an exact cable length to a certain disconnection pattern since this would vary in reality. Instead, the cables are sorted into length intervals. When this is done the full length of the cables is used; the cable objects are not split at the district border. Shorter cables are interpreted as if have been disconnected due to repair or maintenance work while longer cables are interpreted as if have been disconnected due to larger excavation project not necessarily related to repair or maintenance work.

3.4 Reliability and validity
In general, this study has a relatively high reliability of data compared to many other studies in the urban mining field. Partly this is due to the choice of method. The used bottom-up quantification method, although very resource intensive, offers a significantly higher reliability and higher detail of the data material. This since the studied material stock is measured directly instead of being estimated indirectly by e.g. studying the in and outflows of the stock. Also, as few simplifications as possible have been made with the data and the calculations. For instance, complete spatial data of an infrasystem for a whole city has been collected, which in theory should cover every single cable in the whole Linköping power grid for the selected period of time.

Table 2. Distribution of cable lengths from sources of different reliability. A higher number means lower reliability.

<table>
<thead>
<tr>
<th>Data source</th>
<th>Level of data reliability</th>
<th>Cable length (km)</th>
<th>Share of total</th>
</tr>
</thead>
<tbody>
<tr>
<td>Erased cables</td>
<td>4</td>
<td>78</td>
<td>47%</td>
</tr>
<tr>
<td>Crossed cables</td>
<td>3</td>
<td>16</td>
<td>10%</td>
</tr>
<tr>
<td>&quot;Disconnected&quot; cables</td>
<td>2</td>
<td>19</td>
<td>11%</td>
</tr>
<tr>
<td>Post 2000 GIS cables</td>
<td>1</td>
<td>54</td>
<td>32%</td>
</tr>
</tbody>
</table>

There are, however, a few issues regarding reliability that need to be highlighted. Most of the reliability issues are related to the format of some of the original data. For the cables disconnected before 2000 their disconnection status has been noted in different ways during different time periods. A minority of the cables have explicitly been labeled as “disconnected”, or equivalent, while a majority of the disconnected cables instead have been erased from the maps. Despite the erased status of the cables, traces of these cables could still be seen and thus cables could be identified. This does however bring some reliability issues; it is possible that other erased objects, such as bike paths, might wrongly have been identified as cables. Secondly, some disconnected cables have been marked with crosses instead of an explicit label. This notification is used inconsistently and does varyingly refer to a single, a few or all cables in a stack. It is therefore a risk that a few in-use cables might incorrectly have been interpreted and registered as disconnected cables. There is thus three different levels of reliability of data for the cables disconnected before 2000. The distribution of cable length per reliability level is shown in table 2. Almost half of the cable length is in the form of erased cables.

Another issue is related to the missing cable type labels of a majority of the cables. The average metal concentration value assigned to these cable objects reduce the accuracy of the analysis somewhat.
4 Results
In total the subsurface power grid in Linköping contains about 233 tonnes of metal. This is divided between 140 tonnes of copper and 93 tonnes of aluminium. The total length of the disconnected cables is about 166 km. With a total active, in-use system length of about 2,700 km (Krook et al. 2011) the concentration of hibernating cables is about 6 % for the whole urban area.

4.1 Spatial distribution of the hibernating metal stocks
The spatial distribution of the copper and aluminium stocks follow similar patterns, although there are some differences. In general, the more industrial dense districts contain a larger share of the metal stocks. This includes the two most northern districts of Kallerstad and Tornby as well as the western district of Tannefors. For the copper stock similar amounts of copper are located in the residential districts of Ryd and Gottfridsberg (see fig. 3). These two districts are mainly made up of multifamily houses but have a significantly higher copper content compared to the other districts with similar characteristics. This can mainly be explained by a few, but long medium voltage copper cables extending through these districts. These areas do, together with the inner city and the adjoining district of Vasastaden and the main industrial areas of Kallerstad, Tornby and Tannefors, have the copper stocks. Areas

<table>
<thead>
<tr>
<th>District</th>
<th>Building type</th>
<th>Age</th>
<th>District</th>
<th>Building type</th>
<th>Age</th>
<th>District</th>
<th>Building type</th>
<th>Age</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>MFH</td>
<td>B</td>
<td>10</td>
<td>Ind.</td>
<td>B</td>
<td>19</td>
<td>MFH</td>
<td>B</td>
</tr>
<tr>
<td>2</td>
<td>Ind.</td>
<td>B</td>
<td>11</td>
<td>Mörndal</td>
<td>C</td>
<td>20</td>
<td>Ind.</td>
<td>B</td>
</tr>
<tr>
<td>3</td>
<td>Kallerstad</td>
<td>B</td>
<td>12</td>
<td>Vastra Valla</td>
<td>E</td>
<td>21</td>
<td>Lambboholm</td>
<td>C</td>
</tr>
<tr>
<td>4</td>
<td>SFH</td>
<td>B</td>
<td>13</td>
<td>Östra Valla</td>
<td>A</td>
<td>22</td>
<td>Djurgården</td>
<td>SFH</td>
</tr>
<tr>
<td>5</td>
<td>Ryd</td>
<td>B</td>
<td>14</td>
<td>Elvåken</td>
<td>B</td>
<td>23</td>
<td>Berga</td>
<td>MFH</td>
</tr>
<tr>
<td>6</td>
<td>MFH</td>
<td>A</td>
<td>15</td>
<td>Garrison</td>
<td>B</td>
<td>24</td>
<td>Vörsbro</td>
<td>SFH</td>
</tr>
<tr>
<td>7</td>
<td>MFH</td>
<td>A</td>
<td>16</td>
<td>Ramshall</td>
<td>A</td>
<td>25</td>
<td>Björndalen</td>
<td>SFH</td>
</tr>
<tr>
<td>8</td>
<td>MFH</td>
<td>A</td>
<td>17</td>
<td>Hjuluparken</td>
<td>A</td>
<td>26</td>
<td>Hjulsbro</td>
<td>SFH</td>
</tr>
<tr>
<td>9</td>
<td>Ind.</td>
<td>A</td>
<td>18</td>
<td>Yttersjö</td>
<td>A</td>
<td>27</td>
<td>Ulstamora</td>
<td>SFH</td>
</tr>
</tbody>
</table>

*Fig. 3. The spatial distribution of the hibernating copper stock in Linköping. Districts are described in terms of age (A = -1960, B = 1960-1979, C = 1980-) and dominating building type.*
with a large share of single family buildings seems have a lower metal content compared to many of the other districts.

The aluminium stock largely follows the same distribution pattern as the copper stock (see fig. 4). The highest amounts of aluminium can be found in the same three industrial districts. The inner city does also contain a large share of the total aluminium. In contrast to the copper stock, Ryd and Gottfridsberg have a significantly smaller proportion of aluminium compared to copper, this due to the large medium voltage copper cables in the area. As for copper the districts dominated by single family houses have a generally low metal content. Notable exemptions to this are the districts Tallboda and Hjulsbro, where single family houses make up the majority of the buildings while they contain about 4 and 6% respectively of the total aluminium stock each.

Building types seems to have a strong influence on the amount of hibernating metal in an area, for instance most of the industrial areas have the largest shares of hibernating metals in the city. A possible explanation to this is the differing power requirements of different building types and activities; industries might require more power and thus larger conductor dimensions to transmit this power. The larger conductor dimensions that the cables are heavier for a given length and there will thus be more amount of metal present even with the same length of cable (Wallsten et al. 2012).

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Some districts with a large share of “special” buildings, which includes schools, hospitals, institutional buildings etc., have a remarkably low hibernating metal stock. Västra Valla, which holds the city’s university, holds less than 1 % share of either copper or aluminium. Presumably since this area is dominated by only a few but large buildings, while the area has seen little change or increase of exploitation throughout the years. The hospital district, Ekholmen, also shows low levels of hibernating metal despite its neighboring to the inner city.

The aluminium to copper ratio in terms of share of total metal amount is generally quite equal for most of the city districts. Copper has slightly lower shares for most areas because of the high copper content in Ryd and Gottfridsberg. Some districts though have a differing ratio where the aluminium share is either significantly higher or lower than for copper. The areas where the aluminium share is smaller than the one for copper tends to be older areas; for example Vasastaden. Whereas the opposite seems to be true for more newly built areas; e.g. Labohov and Ullstämma, both mainly built during the 1980's. Hence the composition of the hibernating metal stock is affected by age of the area, and in turn the power grid; a newer area gives larger proportions of aluminium in the stock. Aluminium conductors was not introduced in Linköping until the 1970's and is almost exclusively used today for all cables dimensions (Jönsson, 2013), why the share of aluminium is lower in the older areas. Age does also affect the size of the stock; older parts of the city, like the inner city and Vasastaden, generally have more hibernating metal compared to younger parts of the city with similar building composition.

4.2 Comparison with Norrköping

When the hibernating parts of the power grid of Linköping is compared with the one in Norrköping both differences and similarities appear. The overall size of the stock in Linköping, of 233 tonnes, is comparable in size to the 275 tonnes of metal in Norrköping (Wallsten et al. 2012). These stocks are on the other hand quite different in their composition. The Linköping power grid contains significantly larger proportions of aluminium. The hibernating copper to aluminium ratio in Norrköping is 10:1 (Wallsten et al. 2012) whereas the Linköping stock has a ratio of approximately 1.5:1. It must be noted though that Wallsten et al. (2012) uses a differing methodology compared to this study which may explain parts of the different proportions of the stocks.

Table 3. Total quantity of hibernating and in-use copper and aluminium in Linköping and Norrköping respectively.

<table>
<thead>
<tr>
<th></th>
<th>Hibernating (tonnes)</th>
<th>In-Use (tonnes)</th>
<th>Share hibernating of total</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Linköping</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Cu</td>
<td>167</td>
<td>2765\textsuperscript{a}</td>
<td>10%</td>
</tr>
<tr>
<td>Al</td>
<td>97</td>
<td>1210</td>
<td></td>
</tr>
<tr>
<td><strong>Norrköping\textsuperscript{b}</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Cu</td>
<td>250</td>
<td>2000</td>
<td>11%</td>
</tr>
<tr>
<td>Al</td>
<td>25</td>
<td>1210</td>
<td>2%</td>
</tr>
</tbody>
</table>

\textsuperscript{a} Value is from Krook et al. 2011. Value is for the total system length Cu and Al combined.

\textsuperscript{b} The Norrköping values are from Wallsten et al. 2012.

The distribution patterns of hibernating copper and aluminium are quite different between the two cities. In Norrköping, both aluminium and copper are clearly concentrated to the most central parts of the city with a lower concentration in the more peripheral parts (Wallsten et al. 2012). Even though the metal concentrations are high in the central parts in Linköping as well, even higher concentrations are found in the surrounding districts of the
inner city. The concentration of metals to the very center of Norrköping can partly be attributed to the former industrial buildings located in the city center (Wallsten et al. 2012), something that Linköping lack in comparison.

4.3 Disconnection mechanisms in the Linköping power grid

The exact, actual reason for disconnection of the cables in Linköping cannot be examined with the used quantitative method. The patterns for disconnection described by Wallsten et al. (2013) could be used to understand reasons for disconnection. Continuous maintenance and repair of broken or worn-out infrasystem parts do more often result in shorter, isolated sections of disconnected cables, or pipes, described as “dormant cells” by Wallsten et al. (2013). Larger projects not necessarily directly connected to the affected infrastructure, sometimes result in larger, cohesive parts, or “infrastructure coma” (Wallsten et al. 2013). Length of disconnected cable parts could thus be used as an indication for the mechanism behind the disconnection.

The disconnected cables in Linköping have been sorted into length intervals (see table 3) to see the distribution of cables sizes. There seems to be a relatively equal distribution of number of cables between the length categories, with the medium voltage cables as an exception with higher share of longer cables. For total metal weight the longer cable categories, here interpreted as system parts in paralysis, dominate because of their length. While the number is more or less equal between the shorter dormant cells and the longer paralysis parts. When the categories are compared in terms of kg of metal per meter cable the differences in concentration are negligible. The average metal content is thus similar between shorter and longer cables.

Table 4. Distribution of cable lengths, sorted into length intervals.

<table>
<thead>
<tr>
<th>Cable length (m)</th>
<th>Pre 2000</th>
<th>Low voltage</th>
<th>Medium voltage</th>
<th>Total</th>
</tr>
</thead>
<tbody>
<tr>
<td>&lt;10</td>
<td>9%</td>
<td>25%</td>
<td>16%</td>
<td>13%</td>
</tr>
<tr>
<td>10-25</td>
<td>24%</td>
<td>21%</td>
<td>17%</td>
<td>23%</td>
</tr>
<tr>
<td>25-50</td>
<td>27%</td>
<td>23%</td>
<td>10%</td>
<td>25%</td>
</tr>
<tr>
<td>50-100</td>
<td>21%</td>
<td>19%</td>
<td>17%</td>
<td>20%</td>
</tr>
<tr>
<td>100-300</td>
<td>17%</td>
<td>12%</td>
<td>22%</td>
<td>16%</td>
</tr>
<tr>
<td>&gt;300</td>
<td>2%</td>
<td>0%</td>
<td>17%</td>
<td>2%</td>
</tr>
</tbody>
</table>
5 Discussion

As part of an urban infrastructure the Linköping power grid shows a significant presence of hibernating metal. However, after such a hibernating stock of metal has been identified, and quantified, some important questions remain. Partly there is the issue of recovering this metal for a re-use or recycling purpose. Secondly, there is the understanding of how these stocks are formed, how this is affected by the unique characteristics of each city, and also how this accumulation of hibernating metal could be avoided in the future.

By comparing the hibernating metal stock in the power grid in Linköping with the equivalent grid in Norrköping this study has sought to increase the understanding of how these hidden metal stocks are shaped within urban areas. Some of the distribution patterns found in Norrköping (Wallsten et al. 2012) can also be found in Linköping, most notably that there is a higher presence of metal in older parts of the city. The overall amounts of metal in Linköping also seem to correspond to the findings in Norrköping, which could be explained by the comparable size and expanse of the two cities. Further examples would be needed though before any general correlations between city size and metal content could be concluded.

Even though the amount of metal is comparable in the two cities the distribution differs, and so does the composition of the stock. Where Norrköping is characterized by a strong concentration of metal to the most central parts, Linköping has its metal stock more widely distributed throughout the city. In addition to a high metal content in the central area, large amounts are also found in more external industrial areas as well as in pure residential areas. The Linköping stock is also characterized by a significantly larger share of aluminium whereas the copper is dominating in Norrköping. These differences in both composition and distribution increase the importance of each city’s uniqueness. Although it is beyond the scope of this study, the properties and characteristics of a city probably have a significant impact on the hibernating metal stock in the city. Differences in present and past technical systems, the history, density of the city etc. and their relationship with the metal stock could be explored in further studies.

The importance of the methodology in mapping these metals must be noted though. The Wallsten et al. (2012) study in Norrköping have to a large extent used extrapolation for determining the size of the metal stock in the city. Whereas this Linköping study has made use of a relatively more accurate methodology where a majority of the cables have individually been assigned a correct value for metal concentration. It is not known to what extent this affects the results of such a study, but there is a possibility that the values from of the Wallsten et al. (2012) study is either exaggerated or underestimated which must be kept in mind while comparing these and other studies.

Extraction and recovery of hibernating parts of subsurface infrastructures in an urban area is coupled with high cost due to the needed excavation etc. (Krook et al. 2011). However, it could possibly be profitable to remove disconnected cables during maintenance work on other cables (Krook et al. 2011). Since this maintenance work is mainly done in shorter, excavated sections of shafts (Krook et al. 2011), the removal of shorter disconnected cables could possibly be favored. This study of Linköping shows a significant number of shorter hibernating cables; a majority of the cables are shorter than 50 meters. These could possible make up opportunities for recovery in the future using recovery during maintenance in the same shaft.

Even though the shorter cables are more numerous, the longer cables still contain the most amount of metal. This is especially true for the medium voltage cables, whose average length and weight is bigger compared to the low voltage cables. Recovery of these, in some cases over 2 km long, cables could be more problematic using integrated recovery. These cables could however be made accessible during future redevelopment projects as suggested
by Wallsten et al. (2012). This could include transformation of industrial areas into residential areas etc. Since the industrial districts of Linköping have the highest metal content, and a high rate of longer cables, these parts of the metal stock could possibly be made accessible during such a future scenario.

It would also be of importance to avoid an accumulation of these metal amounts in the future. If disconnected cables could be removed from their position before entering a state of hibernation an accumulation of important metals in an inaccessible and “invisible” subsurface storage could be avoided or at least reduced. This would however require actions from different actors depending on why these cables are being disconnected. As the findings of this study show, the disconnected cables are present in various length intervals and thus different actors could be affected. Shorter cables disconnected due to repair and maintenance would for instance have to be removed by the grid owner during such work. Longer cables on the other hand, would require other actors to be engaged as well, such as the municipality or urban planners in such cases where cables are disconnected due to larger projects in the city. Although shorter cables are more numerous, and longer cables contain the most metal, a definitive main reason for disconnection cannot be not be seen in the results of this study.

A considerable hinder for further studies of subsurface, urban infrasystems is the low availability of data. Infrasystem owners do commonly not have a full understanding of the extent and amount of the whole disconnected parts of their infrasystems. Data for disconnected parts may be spread out and also documented using different methods making it very difficult to overview the complete disconnected parts of an infrasystem both spatially and temporally. In the case of Linköping parts of the data for disconnected cables had even been deliberately erased, data that could only be recovered with much effort and time. Also since only cables disconnected from around 1970 and onwards the this study has not completely covered the studied stock from a time perspective.

For future studies of the urban mining potential the method would have to be carefully considered. Although a complete dataset for all disconnected infrasystem parts would give the the best picture it must be weighed against the cost of time for collecting the data. Studies on even larger cities would require proportionally more time for data collection. At the same time many parts of an urban area have relatively low hibernating metal concentrations. Depending on the availability of data, and the needed time for collecting it, simplifications of the method could be appropriate. A possibility could be to focus the studies on areas where the metal content are presumed to be the highest, e.g. industrial areas, and also on areas where the potential for recovery is the greatest. However, the unique characteristics of a city would have to be considered in such a case.
6 Conclusions

- A sizable hibernating metal stock of 140 tonnes of copper and 93 tonnes of aluminium could be identified in the Linköping power grid.

- The identified metal stock is distributed across the whole urban area of the city. With a large portion of the metal is found in the northern industrial areas.

- The distribution pattern of the metal stock in Linköping differs from findings in earlier studies. This can mainly be explained by the presence of a few metal rich cables that depart from the overall pattern.

- The length of the disconnected cables varies, but shorter cables, or dormant cells, are generally more numerous while longer cables are more few. This pattern is interpreted as that continuous repair and maintenance gives rise to a higher number of disconnected cables. The most metal is though situated in the longer cables which contain more metal. These cables are possibly disconnected to a larger due to projects not directly related to repair.

- Significant differences in the distribution patterns of the metal stock is identified when the findings of this study are compared to to earlier studies. Future studies could explore this further.
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I would like to thank Lars Jönsson and Annie Nilsson for their help while I was searching through the archives at Tekniska Verken, also thanks to Tekniska Verken/Utsikt for the generous supply of and access to invaluable data. And thanks to my supervisor Joakim Krook for guidance and valuable feedback during the work with this thesis, and also to Stefan Svanström for his invaluable assistance with GIS.
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Appendix 1 – Maps of Norrköping's hibernating metal stock

The figures A1:1 and A1:2 display the size and distribution of the hibernating copper and aluminium stocks in the subsurface power grids Norrköping. The figures are from Wallsten et al. (2012) and cover both the public and private power cables and AC as well as DC.

Fig. A1:1. Hibernating copper stock in subsurface infrasystems. Map from Wallsten et al. (2012). Used with author's permission.
Fig. A1:2. Hibernating aluminium stock in subsurface infrasystems. Map from Wallsten et al. (2012). Used with author's permission.