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Designing smart, resilient cities for all

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1 Introduction

When taking the solutions demonstrated in the Lighthouse cities from demonstration level to full scale implementation on city level, the effects on the energy system of the city as well as the surrounding energy system are of great importance. The effects of upscaling of demonstrations is generally not linear and when a demonstration is replicated and scaled in a different context the impact can be very different An analysis of the scaling effects of relevant solutions in the RUGGEDISED Lighthouse cities as well as the effects of replication to other cities and aggregate effects is therefore required to fully understand the impact of the demonstrated solutions.

1.1 Scope and objectives of the deliverable

In this deliverable analysis is performed of the effects from scaling the demonstrated solutions in the participating lighthouse cities, Glasgow, Rotterdam and Umeå. The aim is to assess energy system effects when the proposed technologies are scaled up in order to analyse benefits and potential negative effects and investment needs in other parts of the system as a result of the upscaling. The effects are expressed in terms of economic savings and emission reduction. The solutions are also analysed when replicated in the other Lighthouse cities in order to assess the impact of the solutions in cities with other prerequisites.

1.2 Contributions of partners

The analysis for each city has been performed by a local partner in order to facilitate data collection and to ensure knowledge of the local conditions and energy system. In Rotterdam the analysis has been done by the City of Rotterdam, in Umeå by RISE and in Glasgow by Strathclyde University.

1.3 Relations to other tasks and deliverables

Deliverable 6.4 relates especially to the other tasks and deliverables of work package 6 but also to other work packages. The analyses are based upon the contextual analysis and scenarios from task 6.3, which provide input concerning projected further development and deployment of the demonstrated technologies within the cities, with focus on visualising and describing a desirable future. The analyses in T6.4 evaluate the technical, economical and carbon emission potential of upscaling the solutions according to the scenarios. The aim is to deliver more tangible and comparable numbers of the smart solutions to be used as input in the urban innovation platform to support upscaling of smart solutions. Data of the different demonstrations are gathered from WP2, 3 and 4.

Table 1. Relation between D6.4 and other activities in RUGGEDISED

Activity	Relation
WP2	Data collection
WP3	Data collection
WP4	Data collection
T6.1	Feed into the work on innovation platforms
T6.3, D6.3	Scenario analysis of scaling potential

1.4 Structure of the deliverable

Section 1 Introduction, scope and objectives

Section 2 Methodology used in the task

Section 3 Results from scaling and replication analysis

Section 4 Conclusions

Section 5 References

2 Task methodology

The aim of this task is to assess the long-term scaling potential and energy system effects of the smart solutions. Since there are several smart solutions included in each lighthouse city and not all of them have direct effects on the energy system some of them are excluded in this analysis.

2.1 Selection of solutions

The selection of solutions for this analysis has been made with respect to short descriptions of each solution and discussions with the project partners. As mentioned, the ones not directly affecting the energy system e.g. solutions focusing on business models or data platforms, are not included. There are also some overlaps of the smart solutions between the three cities, and in these cases one of them has been selected for modelling, representing also the similar solutions in the other cities. An example of this is the analysis of G2, G4 and G5 solution, EV charging hub battery storage and optimization of the integration of near-site RES which covers the main aspects of the R5, R6 and U6 solutions. All of these solutions aim to install solar PV's on roofs to be able to charge electrical vehicles with renewable electricity. It should be noted that some aspects and details of the specific solutions might not be covered through the analysis of the Glasgow solutions. The smart solutions included for each lighthouse city is presented in the lists below.

- G2, G4 & G5 – EV charging hub battery storage and optimization of the integration of near-site RES
- G2 & G9 – Battery-supported load management in high-rise flats

- R1 Geothermal heat-cold storage and heat pumps
- R2 Thermal energy from waste streams
- R4 Pavement heat cold collector
- R5 DC grid, PV and storage for mobility (covered by G5)
- R6 Smart charging parking lots (covered by G5)
- R8 Energy management

- U2 Peak load variation management and peak power control
- U4 Intelligent building control and end user involvement
- U6 E-charging infrastructure (covered by G5)
- U9 Demand side management

2.2 Analysis of solutions

The methodology and tools used to model or calculate the effects of the different solutions differs between the solutions, as well as the level of detail of the calculations. Some of the solutions are modelled in more detail while others are based on rough estimates. The adopted approach depends on the characteristics of the solutions and the availability of modelling tools and data. Data is gathered through the project partners as well as from other relevant sources. The solutions in Glasgow are handled by University of Strathclyde, solutions in Rotterdam by the city of Rotterdam and solutions in Umeå by RISE. These partners are also the ones responsible for gathering data for the different solutions in their city as well as for the data required to adapt the other cities' solutions to their respective city.

An estimation of the cost effects of the different solutions is included in the analysis and the approach also differs between the solutions due to their setup, the size, stakeholders involved etc. For most of the solutions the investment cost is not representative to a scaled up cost since they are demonstrations, however, for the solution to be upscaled in the future, the investment must have a reasonable pay-off time, e.g. due to reduction in running costs. The purpose of the cost estimations is therefore to give an indication of the possible cost reduction with the solution compared to an alternative cost, which would have been there without the solution. The energy prices used to calculate the possible cost reductions is presented in Table 2. For an easier comparison of the costs, the prices in SEK and £ is converted to Euros. The average exchange rates for 2019 is used for both SEK and £, 1 Euro is equal to 10.5891 SEK (European central bank) and 0.8777 £ (European central bank).

Table 2. Energy prices in Rotterdam, Glasgow and Umeå.

City	District heating price	Electricity price	Natural gas price
Rotterdam [€/kWh]			
Large consumers	0.0504	0.065	0.0288
Small consumers	0.0915	0.25	0.0973
Glasgow [€/kWh]	0.1205	0.1794 (excluding standing charges) 0.2558 (including standing charges)	0.0433
Umeå [€/kWh]	0.0420 (Umeå Energi, 2019)	0.0799 (excluding variable transmission charges) 0.0973 (including variable transmission charges) (Umeå Energi)	NA

The approach used for calculating the CO_2 emissions is similar to the cost calculations. It is only the emissions during the use phase that are included, and the emissions with the solution implemented are compared to the alternative level of emissions without the solution. The emission factors used for the CO_2 emission effects for the solutions are presented in Table 3.

Table 3. CO_2 Emission factors used for heating, electricity and gas in Rotterdam, Glasgow and Umeå.

City	District heating	Electricity	Natural gas
Rotterdam [g/kWh]	81.22	430	225 (90% boiler efficiency)
Glasgow [g/kWh]	200	277 (Carbon footprint, 2019)	210
Umeå [g/kWh]	48.06 (Umeå Energi, 2019)	50 (Energi & klimatrådgivningen, 2018)	NA

The different solutions and the methodology used for the analysis is described in more detail for each solution in Chapter 3.

2.3 Upscaling of solutions

The upscaling of the solutions is partly based on the scenarios presented in deliverable 6.3. It is the dimension of physical presence that is considered in this analysis, and adjustments to the scenarios have been made when necessary. The scenarios only include an estimation of the upscaling potential for the solutions demonstrated in the respective lighthouse cities. Since this analysis aims to include the aggregate effects of upscaling all solutions in each city, the upscaling potential for the other solutions is estimated based on the requirements of each solution. The effects are expressed in terms of cost, energy use and change in emissions.

3 Results

This section includes a description of the demonstrations related to the energy system that is implemented in the three lighthouse cities. The upscaling potential of these demonstrations is also analysed for all three cities.

3.1 Rotterdam solutions

Three smart solutions (R1, R2, R4) are being implemented within the Smart Thermal Grid (STG). R3 is not guaranteed to be implemented within RUGGEDISED and is therefore not analysed. The implementation of the different solutions is closely related to each other. This is illustrated in Figure 1 where all Rotterdam solutions are included. The smart solutions described below focus on the following buildings:

- Existing AHOY Exhibition Center
- New Rotterdam Ahoy International Congress Center (ICC)

These buildings are now connected through the backbone of the smart thermal grid, the hotel and cinema are to be developed and are in this report seen as upward potential. Energy management (R8) will further optimize the energy efficiency of the buildings and the STG.

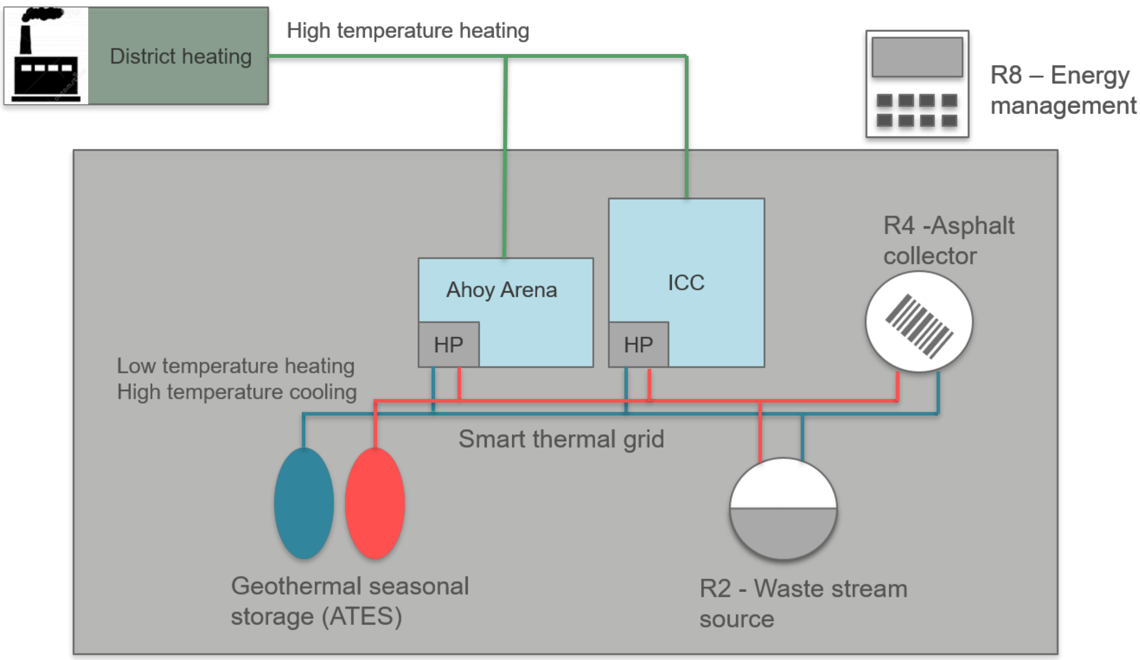

Figure 1. Illustration of the Rotterdam solutions and their connection.

The energy prices used in the cost calculations are presented in Table 2 in section 2.2 where the prices for Rotterdam represent the actual market prices of today (2020). The prices are based on the delivery tariff, excluding fixed fees for e.g. the connection. For small consumers the prices include all taxes: energy taxes and sustainability tax and VAT. For the large consumers the prices are excluding VAT.

The CO_2 emission factors used to calculate the carbon savings are presented in Table 3 in section 2.2.

3.1.1 Upscaling of Rotterdam solutions

The upscaling of the Rotterdam solutions R1, R2, R4 and R8 are presented here and calculated for the roll out in Glasgow, Umea and Rotterdam. This roll out is done city wide, and for each solution it's stated on which criteria, e.g. buildings, and which assumptions are made.
It should be noted that this analysis is a theoretical technical potential, based however on educated guesses on technical roll out potential. For example: for R4, the pavement heat cold

collector, it's assumed that 35% of the road surface is asphalt of which 60% is suitable for this solution. Also an energy loss factor is applied of 60% to correct for shading of surrounding buildings, pump energy for the system and efficiency of the heat exchanger.

3.1.2 Solution R1 – Geothermal heat-cold storage and heat pumps

This solution consists of a thermal grid connecting large buildings in the Heart of South district. In the first phase the Exhibition Center Ahoy is connected with a backbone to the International Congress Center (ICC). **The aim of this solution is to enable local heat-cold exchange to maximise the use of waste heat-cold through geothermal storage (ATES) and lower the total cost of ownership.** In a later phase all buildings will be connected by a low temperature grid and heat pumps supplying the required heat and cooling. The waste heat of the condenser is fed back into the thermal grid. High temperature cooling is provided directly from the smart geothermal grid.

Since heat is available already through the high temperature district heating (90 °C), the design of the Smart Thermal Grid is based on the cooling demand and on optimising the use and thermal balance of the existing ATES. Solutions R2 and R4 feed into R1 via the Smart Thermal Grid to supply extra heat to the ATES for reaching this balance. R1 includes the required Smart Thermal Grid to make exchange of heating and cooling between sources (R2 and R4) and buildings possible and between buildings themselves.

The amount of cooling supplied by the Smart Thermal Grid is designed in close collaboration with all stakeholders. Sharing of cooling capacity between the different stakeholders is one of the main advantages with this solution. It saves on investing and exploitation costs of cooling systems. In fact it is possible due to different timings of big events in each building, to shift cooling-capacity between the buildings. For the Exhibition Center Ahoy the main driver of cooling demand is the attendance of events. In order for them to understand what the Smart Thermal Grid would do, it was necessary to translate the amount of cooling available to air conditions for a certain number of visitors for a certain outside temperature. Project Partner Ballast Nedam provided a breakdown what the new international conference centre (ICC) is expected to demand cooling for a given number of visitors and a given outside temperature (ranging from 26 °C to 30 °C). Table 4 shows the results. The yellow cells indicate the amount of cooling in kW that could have been provided without the R1 solution in place, which is below 2100 kW. With the R1 solution in place it is also possible to cover the cooling demand in the cells not marked with yellow through the use of both thermal storage and the cooling capacity available at AHOY exhibition center.

Table 4. Power (kW) needed for cooling based on outside temperature and visitor numbers.

Occupancy	Cooling demand at different outside temperatures [kW]		
	30 °C	**28 °C**	**26 °C**
100% occupancy at ICC and at RTM stage 7000 people	**2774**	**2319**	**1812**
100% occupancy at ICC and at RTM stage 2750 people	**2315**	**1904**	**1494**
85% occupancy at ICC and at RTM stage 7000 people	**2549**	**2143**	**1678**
85% occupancy at ICC and at RTM stage 2750 people	**2090**	**1728**	**1174**
75% occupancy at ICC and at RTM stage 7000 people	**2399**	**2025**	**1588**
75% occupancy at ICC and at RTM stage 2750 people	**1940**	**1610**	**1154**

This breakdown was scaled up for all different buildings of the Ahoy complex. These numbers were juxtaposed to the available power planned for the Smart Thermal Grid. In the end the choice was made for a system based on a temperature in the ATES of 11 °C, two heatpumps of 550 kW and three chillers (two at the existing Ahoy and one at the new congress center ICC) of 950 kW each. The optimal amount of cooling exchange between Ahoy and ICC was set at 1400 kW. With this amount, a fully packed conference centre can get **enough cooling up until an outside temperature of 30 °C outside**. In the business as usual scenario, only enough **cooling until 26 °C would have been available**. This evident benefit convinced the end users to commit to and invest in the project.

The process described above was a **co-creation** between the end user (Ahoy), the building owner (muncipality of Rotterdam), the building company (Ballast Nedam) and the investor/energy company (Eneco).

3.1.2.1 Rotterdam system analysis

The possibilities of upscaling this solution within Rotterdam is not one to one the same as the solution being implemented in Heart of South. Since there is only one location in the city with the specific building-setting of an exhibition center and a congress center with their specific energy consumption and pattern.

Upscaling of this solution is also suitable for larger buildings with a relatively high cooling demand, typically present in each city are office buildings. Therefore, the upscaling potential is calculated for office buildings in the three cities. In Rotterdam it is estimated that this solution **can be implemented in 20% of the existing office buildings**. For this solution it is essential that the energy system within the buildings can use low temperature heating and high temperature cooling. Also, the buildings have to be interconnected by a backbone/smart thermal grid. In Rotterdam the upscaling situation is summarised in Table 5.

Table 5. Results of upscaling the Geothermal heat-cold storage and heat pumps in Rotterdam.

Office floor area upscaling	723 810	m2
Specific heating demand	70.2	kWh/m^2
Specific cooling demand	8.9	kWh/m^2
Total heating demand	50 811	MWh
Total cooling demand	6 442	MWh
Energy consumed for heating	13 130	MWh
Energy consumed for cooling	849	MWh
Average COP heating	3.9	ratio
Average COP cooling	7.6	ratio
Additional heat needed regeneration	46 141	MWh
Additional heat by District Heating	5 081	MWh

The energy consumed for heating is all electric energy needed for the heating system: the heat pump system, with a Coefficient Of Performance (COP) of 3, the pumping energy for the ATES wells, the electric energy for pumping the water in the grid and the electric energy for the distribution part in the district heating grid. In addition to the energy consumed for heating is 10% of the heat demand supplied by district heating. The Average COP heating is calculated as the overall performance of the system, total heating demand divided with the energy consumed for heating.

The energy consumed for cooling consists of all the electric energy needed for: the compression chillers, the pump energy for the cold part of the ATES wells, the electric energy for pumping the water in the grid and the electric energy for the distribution part. **80% of the cooling is produced by the R1 solution, 20% by conventional compression chillers.**

The additional heat needed regeneration is the heat required to keep the thermal balance in the ATES. The demand for additional heat needed regeneration is dependent on the large disbalance in heating and cooling demand of the buildings connected to the R1 solution. The heat needed can be supplied from different sources to the ATES, e.g. the R2 and R4 solutions but also with heat from district heating or dry coolers.

3.1.2.2 Umeå system analysis

The upscaling potential of this solution in Umeå is derived from the available office buildings in the city. The **upscaling factor is 25% of the office building stock in the city centre**. The result of upscaling this solution in Umeå is presented in Table 6.

Table 6. Results of upscaling the Geothermal heat-cold storage and heat pumps in Umeå.

Office floor area upscaling	112 619	m2
Specific heating demand	135.0	kWh/m^2
Specific cooling demand	10.0	kWh/m^2
Total heating demand	15 204	MWh
Total cooling demand	1 126	MWh
Energy consumed for heating	3 929	MWh
Energy consumed for cooling	148	MWh
Average COP heating	3.9	ratio
Average COP cooling	7.6	ratio
Additional heat needed regeneration	14 513	MWh
Additional heat by District Heating	1 520	MWh

3.1.2.3 Glasgow system analysis

The upscaling potential of this solution is specified by Glasgow based on the existing office building stock. **The upscaling factor is 25% of the total office building stock**. The result of upscaling this solution in Glasgow is presented in Table 7.

Table 7. Results of upscaling the Geothermal heat-cold storage and heat pumps in Glasgow.

Office floor area upscaling	251 503	m2
Specific heating demand	91.0	kWh/m^2
Specific cooling demand	9.0	kWh/m^2
Total heating demand	22 887	MWh
Total cooling demand	2 264	MWh
Energy consumed for heating	5 914	MWh
Energy consumed for cooling	298	MWh
Average COP heating	3.9	ratio
Average COP cooling	7.6	ratio
Additional heat needed regeneration	21 346	MWh
Additional heat by District Heating	2 289	MWh

3.1.2.4 Cost Analysis

Looking at the cost benefit, each city has its own reference system for thermal energy which will be replaced by this solution. However, it will not be replaced by this solution alone, as stated above, this solution requires additional heat for regeneration from e.g. the R2 and R4 solutions. This cost calculation includes the cost for energy consumed for heating and cooling and additional heat by district heating, compared to the reference energy source in each city, which could be replaced when upscaling this smart thermal grid. For Rotterdam and Glasgow this reference is typically natural gas fired boilers, for Umea it is district heating. The investment costs for the smart thermal grid is not included.

The yearly exploitation benefits on energy are:
Rotterdam small consumers: 1 328 862 €, 24% lower than the reference exploitation
Glasgow small consumers: - 964 863 €, -97%, this means roughly doubling the exploitation
Umeå small consumers: 191 008 €, 28% lower than the reference exploitation

It's remarkable that for **Glasgow there is a heavily negative cost benefit in the exploitation**. This is explained by the **high prices for electricity and low prices of natural gas**. So, shifting away from natural gas towards electricity and district heating is financially not beneficial in the exploitation.

3.1.2.5 Carbon Effects

The carbon effects for this solution include shifting from the reference system in each city to the amount of electrical energy and district heating presented as the energy consumed for heating, cooling and district heating in Table 5, Table 6 and Table 7 for each city.

The carbon emission effects of upscaling R1 in **Rotterdam** gives a reduction of 5 932 tonnes CO_2 per year. This is a **reduction of CO_2 of 48 %** compared to the reference system.

Upscaling this solution in **Glasgow** reduces 2 837 tonnes CO_2 per year. This is a **reduction of CO_2 of 57 %** compared to the reference system.

With an upscaling of this solution in **Umea** it reduces 473 tonnes CO_2 per year. This is a **reduction of CO_2 of 63 %** compared to the reference system.

3.1.3 Solution R2 – Thermal energy from waste streams

The aim of this solution is to recover heat from the municipal sewage water in a pumping station through a heat exchanger and use it for heating buildings directly or store it in the seasonal aquifer thermal storage.

The demonstration site at pumping station Wolphaertsbocht, which has been built before RUGGEDISED, has shown that thermal energy can be extracted according to the specifications given by the wastewater heat exchanger manufacturer Uhrig. Since wastewater is especially warm in summertime, it is beneficial to combine this solution with R1, the heat cold storage system (ATES).

This solution is mainly suitable for larger municipal wastewater systems, since the system requires enough waterflow to be able to extract enough heat. For this a minimum daily flow is recommended of 2000 m^3 water per day per pumping station. Another requirement for this solution is to have a basin in the pumping station where the wastewater is collected with a minimum size of 25 m^2. In the Rotterdam case a mixed sewage system is looked at, which include; black (toilet), grey (shower etc) and rainwater. Due to the large flow rates, the daily variation of domestic wastewater, with peaks in the morning and evening, are not disturbing the energy potential. The minimum flow rate is guaranteed at this scale.

Another solution could be to extract heat from the municipal sewage pipes, free flow as well as the pressure pipes. Especially interesting is to recover waste heat at building scale, since the temperature is then the highest, e.g. in shower drains. Another concentrated stream with a very large flow rate and high temperature is at the effluent of wastewater treatment plants. For this report we only look for extraction from the basin of the pumping station. See Figure 2 for the three different scales from which thermal energy can be recovered.

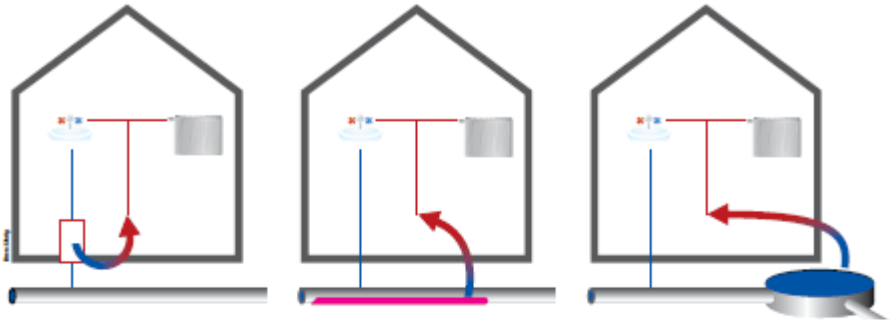

Figure 2. Different scales for heat recovery: in the building, from the municipal wastewater and at the effluent of the wastewater treatment plant.

3.1.3.1 Temperature of wastewater

The temperature next to the flow rate is of utmost importance for the efficiency of this solution. Therefore, it is good to look for a location where buildings which use a lot of hot tap water or other hot water are connected to the sewage system. Most of the times domestic areas are interesting because of the large amount of hot water relative to cold water: almost 70% is heated water varying from washing machines to showers, etc.

As mentioned, the wastewater is hottest in the summer. In Rotterdam it is shown from measurements that the daily mean temperature varies between 10 °C in wintertime and 23 °C in summertime. During winter, it is also possible to recover cooling energy. For this report this is not considered since the Rotterdam solution as part of the STG asks only for extra heat capacity. See Figure 3 for the different sewage temperatures as measured at demonstration pumping station Wolphaertsbocht.

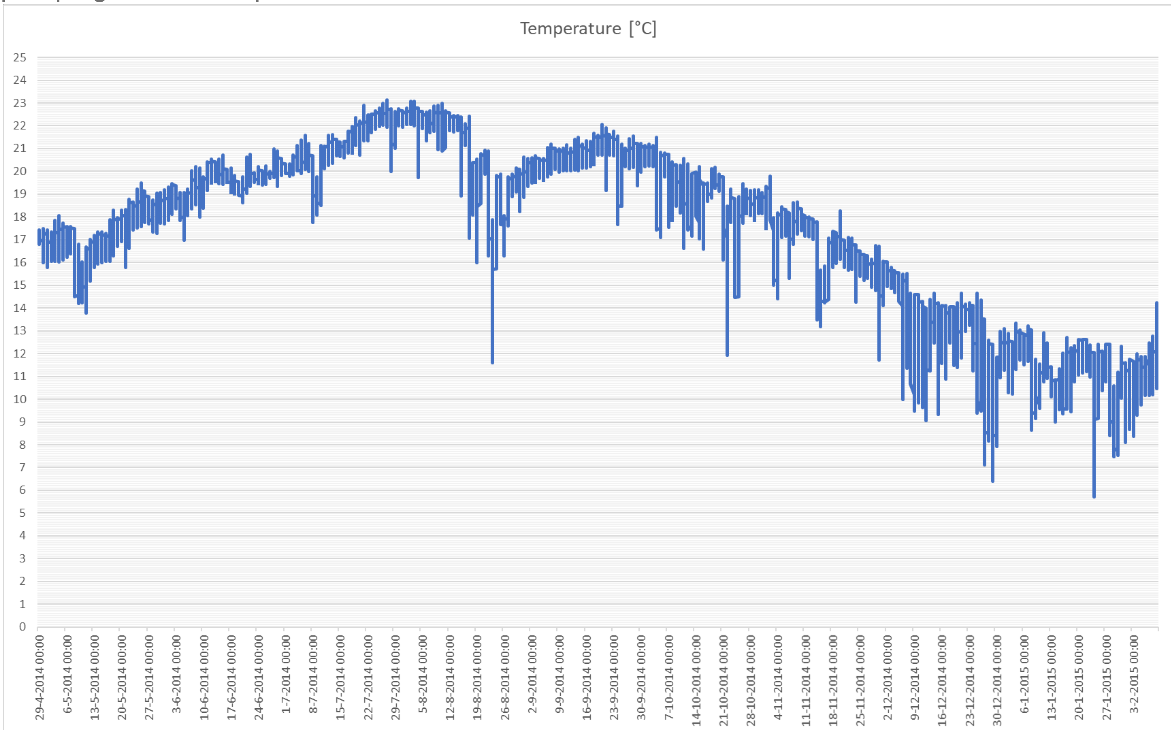

Figure 3. Temperature of wastewater at pumping station Wolphaertsbocht.

Since the wastewater treatment plant needs the temperature of the wastewater to be at a certain level to clean it efficiently with a bacteriological process, the influent temperature should not be lower than 10°C in general. So especially with heat exchangers close to the treatment plant this should be kept in mind, since then the wastewater will not heat up again because there is not much other wastewater flowing in to heat up the sewage water. However, the effect of heat extraction at the pumping station in the Rotterdam solution (Zuiderparkweg) is low: it lowers the temperature with 0,7 °C, which could be an issue in the worst condition at wintertime, during short periods.

In Figure 4 the sewage water temperature at the influent (Water T influent) at the Rotterdam sewage treatment plant can be seen. It varies between 9 and 23 °C. Yearly average temperature is 16 °C.

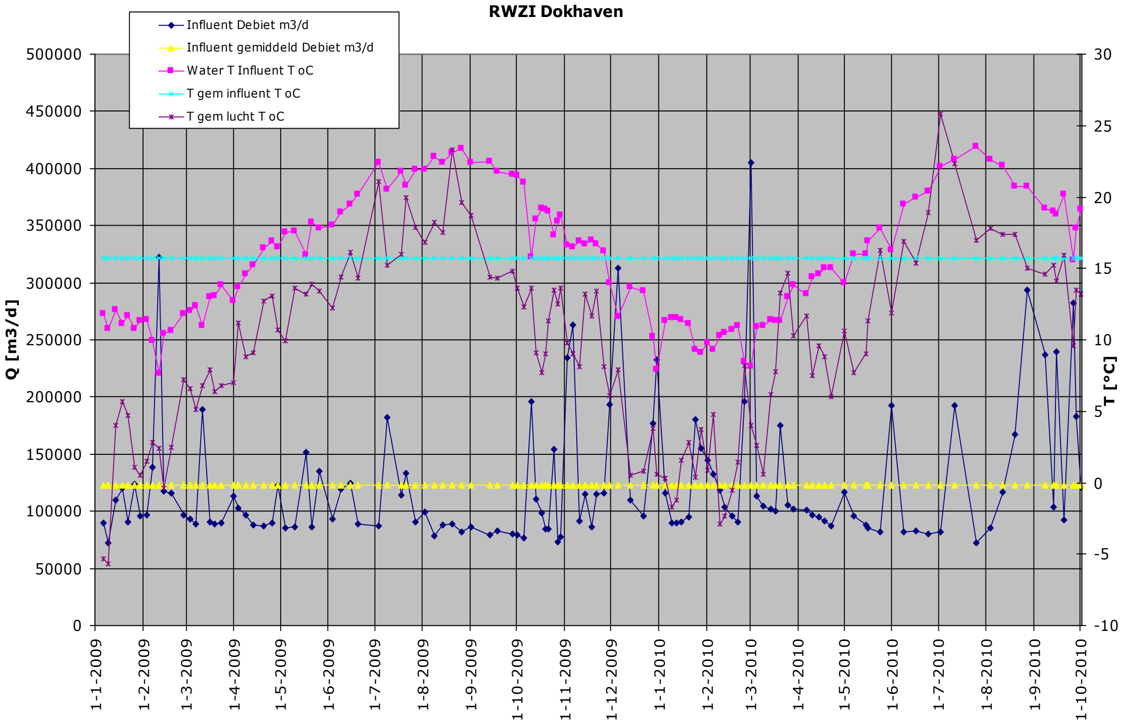

Figure 4. Temperature of wastewater at the inlet (influent) of the wastewater treatment plant.

This solution is due to the low temperatures of the heat, only suitable for low temperature heating systems. After recovery with the heat exchanger at the bottom of the basin, the temperature of the water can be heated to 50-55 °C with an electrical heat pump. It is important to acknowledge that the heat pump system is not regarded in this analysis. Furthermore, the energy potential is robust since it is calculated for a fixed temperature of the wastewater of 13 °C all year round. This is done to be able to guarantee the Thermal output [kW].

3.1.3.2 Rotterdam system analysis

The upscaling potential for Rotterdam depends on the number of pumping stations which are dealing with enough flow and which have enough accessible space available to implement this solution. In Rotterdam there are **20 pumping stations** which are more or less **comparable to the RUGGEDISED location** at our RUGGEDISED solution pumping station Zuiderparkweg. Therefore, the potential and criteria are **scaled with a factor 20 for this analysis**. However, this solution does also require a connection to a low temperature grid to be able to make use of the heat extracted at the pumping stations. See Table 8 for the main results of the upscaling calculations. The thermal output is the net output which can be extracted, so it includes losses for the heat exchangers, the energy use of the circulation pump, and some losses from lower working hours due to low temperatures. This total effect in losses is estimated to be 40% and is already accounted for in the potential energy calculations. The supplier of the wastewater heat exchanger did already take into account a loss of another 40% due to biofilm on the heat exchanger. Since the Rotterdam solution is not built yet (January 2020), the results and calculations below cannot be verified yet. Due to all the losses considered with a pessimistic assumption, the results are expected to be better in a real-life situation.

Table 8. Results of upscaling to 20 pumping stations in Rotterdam.

Total flow pumping stations	79 488.0	m^3/day
Thermal output	1 584.0	kW
Energy output	13 875.8	MWh
Specific energy output per waterflow	174.6	kWh/m^3
Specific energy output per inhabitant	21.7	kWh/inhabitant

3.1.3.3 Umea system analysis

Umeå has fewer pumping stations that suit the needed specifications of minimal flowrate and a basin, **five pumping stations** compared to 20 in Rotterdam. The total flow is roughly four times smaller, which makes the average flow in all pumping stations almost the same as in Rotterdam, around 4000 m^3 wastewater per day.

See Table 9 for the main results of the calculations for the five Umea stations for their potential. **Next to the smaller scale, the thermal and energy output results are a bit lower than in Rotterdam, due to an estimated lower sewage water temperature**. The lower thermal and energy output effect is estimated to be reduced by 15% compared to the Rotterdam case. The thermal output is the net output which can be extracted, so it includes losses for the heat exchangers, the circulation pump-energy, and some losses from lower working hours due to low temperatures. This total effect in losses is estimated to be 40%. This is the upscaling potential of recovering energy from wastewater in Umeå with this technology. However, to be able to utilize this energy, a low temperature grid within the city is also required.

Table 9. Upscaling potential of R2 solution in Umeå.

Total flow pumping stations	20 579.0	m^3/day
Thermal output	348.6	kW
Energy output	3 053.5	MWh
Specific energy output per waterflow	148.4	kWh/m^3
Specific energy output per inhabitant	24.0	kWh/inhabitant

3.1.3.4 Glasgow system analysis

The Glasgow situation is derived from the Rotterdam solution. The total flow at the pumping stations, presented in Table 10, **is scaled down from the number of inhabitants of Glasgow compared to Rotterdam.** Since these figures are comparable, the results are almost the same for the total flow. **The thermal and energy output is estimated to be 10% lower than in Rotterdam due to an estimated lower sewage water temperature**. The number of pumping stations is with 19,6 almost identical to Rotterdam (20). The main results of the upscaling in Glasgow is presented in Table 10. The Thermal output is the net output which can be extracted, so it includes losses for the heat exchangers, the circulation pump-energy, and some losses from lower working ours due to low temperatures. This total effect in losses is estimated to be 40%.

Table 10. Upscaling potential of R2 solution in Glasgow.

Total flow pumping stations	77 749.2	m^3/day
Thermal output	1 394.4	kW
Energy output	12 215.1	MWh
Specific energy output per waterflow	157.1	kWh/m^3
Specific energy output per inhabitant	19.5	kWh/inhabitant

3.1.3.5 Cost analysis

Looking at the cost benefit, each city has its own reference system for thermal energy which will be replaced by this solution. However, it will not be replaced by this solution alone, but with a low temperature grid, represented with solution R1, to where the recovered heat from this solution is fed into. This cost analysis **does not include the cost for the low temperature grid**, it is instead **covering the exploitation benefits on energy compared to the reference energy source**. For Rotterdam and Glasgow this reference is typically natural gas fired boilers, for Umea it is district heating. The different costs for large and small consumers in Rotterdam assumes that it is either only large consumers that implement this solution or only small consumers that implement this solution, so the cost saving potential is not the sum of the two.

The yearly exploitation benefits on energy are then:

Rotterdam large consumers:	399 624 €
Rotterdam small consumers:	1 350 119 €
Glasgow small consumers:	528 914 €
Umeå small consumers:	128 247 €

3.1.3.6 Carbon effects

The carbon emission effects of upscaling R2, thermal energy from waste streams, in **Rotterdam** gives a reduction of **3 122 tonnes CO_2 per year**.

Upscaling this solution in **Glasgow reduces 2 565 tonnes CO_2 per year**.

With an upscaling of this solution in **Umeå it reduces 147 tonnes CO_2 per year**. The effects in Umeå is less pronounced than in both Rotterdam and Glasgow, both due to lower upscaling potential and the lower emission intensity of the reference system in Umeå.

3.1.4 Solution R4 – Pavement heat cold collector

The aim of this solution is to recover warmth from asphaltic pavement, where the surface temperatures can reach 60 to 65 °C during summer. Tubes are integrated in the asphalt-layer and in summertime the heat from the asphalt is recovered by cold water that is pumped through the tubes. The heat is stored in the R1 solution: the seasonal heat cold storage system. It then functions as a solar collector and cools down the surface. In that sense it has a positive effect on the Urban Heat Island effect, which is especially of importance in dense city areas. In winter, warm water is pumped through the tubes to keep the temperature of the asphalt above 0 °C which avoids snow and ice on the pavement. Due to lowering the bandwidth of the minimum and maximum temperature of the asphalt, the lifetime extension is estimated on 150%: less crack-forming in winter due to freezing of water in the asphalt and less plastic deformation in summer. Since the asphalt collector especially heats up in summertime, it is beneficial to combine this solution with R1, the heat cold storage system (ATES) for seasonal storage. See Figure 5 for the Road Energy System which was constructed in 2013 by company Ooms Avenhorn at our demonstration site at pumping station Wolphaertsbocht.

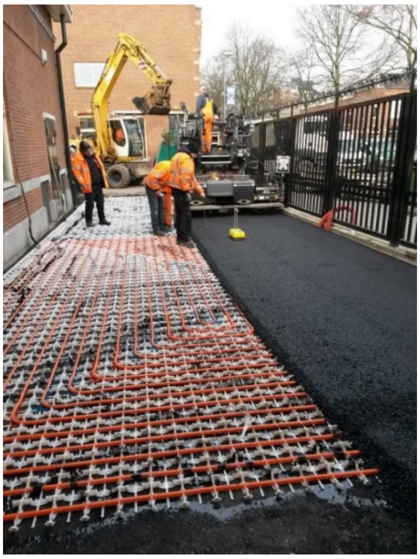

Figure 5. Asphalt collector at demonstration site, pumping station Wolphaertsbocht.

In Figure 6 it can be seen how the asphalt collector collects heat in summer for storage in the hot part of the hot-cold seasonal storage system below the surface in the groundwater layer. In winter cooled down heating system water from the building is pumped through the asphalt collector and cools down further, after which it can be stored in the cold part of the hot-cold seasonal storage system below the surface.

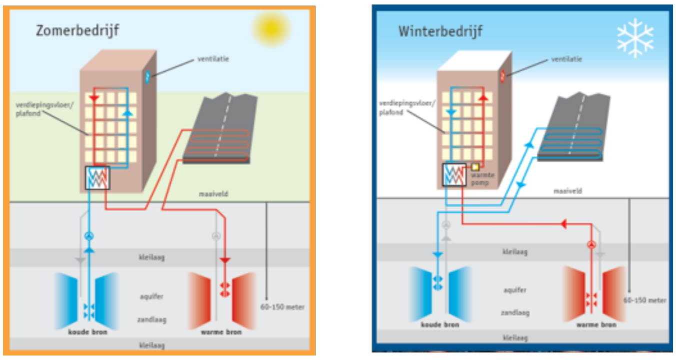

Figure 6. Asphalt collector summer and winter situation with seasonal hot-cold storage.

3.1.4.1 Rotterdam system analysis

The possibilities of upscaling this solution in Rotterdam are depending on:

- Type of road surface, should be asphalt
- Location in city, should be close to energy consumer or Smart Thermal Grid
- Losses due to shading of buildings, trees, etc.
- Energy losses: circulation pump and heat exchanger efficiency

It's assumed that **35% of the road surface is asphalt of which 60% is suitable for this solution**. Also, an energy loss factor is applied of 60% to correct for shading of surrounding buildings, pump energy for the system and efficiency of the heat exchanger. By calculating the specific energy output per m^2, this solution can easily be scaled with other road surface availability assumptions. In Rotterdam the upscaling situation is summarised in Table 11.

Table 11. Results of upscaling the pavement heat cold collector in Rotterdam.

Total road length	2 127.0	km
Yearly sun-energy supplied	1 152.0	kWh/m^2
Suited road area (asphalt)	3 126 690	m^2
Specific energy output per m^2	134.4	kWh/m^2
Energy output	420.4	GWh

3.1.4.2 Umea system analysis

The upscaling potential of this solution in Umeå is derived from the Rotterdam solution where results are scaled down from the Rotterdam city area compared to Umeå. Furthermore, the correction factor is different for the yearly sun-energy supplied. The possibilities of upscaling this solution in Umeå is dependent on the same factors as in Rotterdam. The result of upscaling this solution in Umeå is presented in Table 12.

Table 12. Results of upscaling the pavement heat cold collector in Umeå.

Total road length	314.2	km
Yearly sun-energy supplied	851.0	kWh/m^2
Suited road area (asphalt)	461 832	m^2
Specific energy output per m^2	99.3	kWh/m^2
Energy output	45.9	GWh

3.1.4.3 Glasgow system analysis

The upscaling potential of this solution are scaled down from the Rotterdam city area compared to Glasgow. Furthermore, the correction factor is different for the yearly sun-energy supplied to the road surface. The possibilities of upscaling this solution in Glasgow is dependent on the same factors as in Rotterdam. The result of upscaling this solution in Glasgow is presented in Table 13.

Table 13. Results of upscaling the pavement heat cold collector in Glasgow.

Total road length	1 707.5	km
Yearly sun-energy supplied	926.0	kWh/m^2
Suited road area (asphalt)	2 509 958	m^2
Specific energy output per m^2	108.1	kWh/m^2
Energy output	271.3	GWh

3.1.4.4 Cost analysis

As stated for the other solutions in Rotterdam, this cost analysis assumes that the low temperature grid is in place and the calculated cost savings is in comparison with the alternative cost of heating, present in the cities right now. It does not include the investment cost of the required equipment, instead it indicates the scope for the investment.

The different costs for large and small consumers in Rotterdam assumes that it is either only large consumers that implement this solution or only small consumers that implement this solution, so the cost saving potential is not the sum of the two.

The yearly exploitation benefits on energy are:
Rotterdam large consumers: 12 106 540 €
Rotterdam small consumers: 40 901 620 €
Glasgow small consumers: 11 745 070 €
Umeå small consumers: 1 926 430 €

3.1.4.5 Carbon effects

The carbon emission effects of upscaling R4, pavement heat cold collector, in **Rotterdam** gives a reduction of **94 582 tonnes CO_2 per year**.

Upscaling this solution in **Glasgow reduces 56 962 tonnes CO_2 per year**.

With an upscaling of this solution in **Umeå it reduces 2 204 tonnes CO_2 per year**. The effects in Umeå is less pronounced than in both Rotterdam and Glasgow, both due to lower upscaling potential and the lower emission intensity of the reference system in Umeå.

3.1.5 Solution R8 – Energy management

This solution looks at the management of all energy streams between buildings in order to **optimize energy distributions between buildings** e.g. minimize peak loads and reduce energy losses. This requires that the buildings are connected through a low temperature grid. All energy-data from the buildings and sustainable sources in the area, such as solar energy and thermal energy production, are gathered and analysed so that demand and supply of energy can be optimized.

The energy management system leads to a 15% reduction of heating, cooling and electrical energy consumption. This improvement is partly caused by behavioural changes due to better understanding of the system due to real time feedback to building operators and more awareness, but also from a technical point of view due to:

- Better demand and supply matching between buildings so thermal energy can be exchanged real time instead of storing it in the seasonal storage (ATES).
- Optimized use of locally produced solar energy. This saves on national grid losses and reduces the peak load on the national high voltage grid.

- Reduced peak demand by reducing the needed power of thermal cooling capacity by sharing installed cooling capacity between buildings via a high temperature cooling grid.

3.1.5.1 Rotterdam system analysis

For the Rotterdam scale up potential it is assumed that **30% of all buildings, residential and business,** are suitable for this solution. For the business buildings Rotterdam looks for buildings built before 1976. See Table 14 for details of the calculation.

Table 14. Results of upscaling of the Energy management solution in Rotterdam.

	Business buildings	Residential buildings
Energy demand heating [kWh/m^2]	96.7	145.0
Energy demand cooling [kWh/m^2]	9.7	0
Energy demand electricity [kWh/m^2]	86.6	30.9
Area of buildings [m^2]	701 849	1 605 120
Higher energy efficiency	15%	15%
Energy reduction heating [GWh]	10.18	34.91
Energy reduction cooling [GWh]	1.02	0
Energy reduction electricity [GWh]	9.12	7.44

3.1.5.2 Umea system analysis

For the Umea scale up potential it is assumed that **25% of all buildings, residential and business, in the city centre** of Umeå are suitable for this solution. See Table 15 for details of the calculation.

Table 15. Results of upscaling of the Energy management solution in Umeå.

	Business buildings	Residential buildings
Energy demand heating [kWh/m^2]	135.0	130.0
Energy demand cooling [kWh/m^2]	10.0	0
Energy demand electricity [kWh/m^2]	98.0	41.7
Area of buildings [m^2]	112 619	152 075
Higher energy efficiency	15%	15%
Energy reduction heating [GWh]	2.28	2.97
Energy reduction cooling [GWh]	0.17	0
Energy reduction electricity [GWh]	1.66	0.95

3.1.5.3 Glasgow system analysis

For the **Glasgow scale up potential it is assumed that both residential and business buildings can scale up according to the Rotterdam potential and specifications**. The total area of the buildings is scaled down from the number of inhabitants of Rotterdam compared to Glasgow. See Table 16 for details of the calculation.

Table 16. Results of upscaling of the Energy management solution in Glasgow.

	Business buildings	Residential buildings
Energy demand heating [kWh/m^2]	96.7	145.0
Energy demand cooling [kWh/m^2]	9.7	0
Energy demand electricity [kWh/m^2]	86.6	30.9
Area of buildings [m^2]	686 496	1 570 008
Higher energy efficiency	15%	15%
Energy reduction heating [GWh]	9.96	34.15
Energy reduction cooling [GWh]	0.996	0
Energy reduction electricity [GWh]	8.92	7.28

3.1.5.4 Cost Analysis

Looking at the cost benefit, each city has its own reference system that is affected by the solution. For Rotterdam and Glasgow this reference heating system is typically natural gas fired boilers, for Umea it is district heating. For all three cities the reference cooling system is assumed to be a cooling machine with a COP of 2.7. **The scaling potential is assumed to be similar for Rotterdam and Glasgow, while the scaling potential is assumed to be almost 9 times smaller for Umeå, which explains why both the reduction in cost and emissions of this solution is less pronounced in Umeå.** The different costs for large and small consumers in Rotterdam assumes that it is either only large consumers that implement this solution or only small consumers that implement this solution, so the cost saving potential is not the sum of the two.

The yearly exploitation benefits on energy are then:

Rotterdam large consumers:	2.400 M€
Rotterdam small consumers:	8.622 M€
Glasgow small consumers:	9.555 M€
Umea small consumers:	0.481 M€

3.1.5.5 Carbon effects

The carbon emission effects of upscaling R8, Energy Management, in **Rotterdam** gives a reduction of **18 780 tonnes CO_2 per year**.

Upscaling this solution in **Glasgow reduces 13 850 tonnes CO_2 per year.**

With an upscaling of this solution in **Umea it reduces 390 tonnes CO_2 per year**.

3.2 Umeå solutions

There are three smart solutions demonstrated in Umeå included in this section. The solutions U2, U4 and U9. The solution U6 is covered by the G5 solution and presented in section 3.3.2. The energy prices used in the cost calculations in Umeå is presented in Table 2 in section 2.2 where the Umeå prices represent the average prices of 2019 by Umeå Energi. The electricity price includes purchase price, green certificates (Umeå Energi), taxes as well as the variable grid fees (Umeå Energi, 2020). The CO_2 emission factors used to calculate the carbon savings is presented in Table 3 in section 2.2.

3.2.1 Upscaling of solutions in Umeå

A general assessment of the upscaling potential of each solution is presented in Deliverable 6.2. The upscaling potential is defined for four different areas in Umeå; University area, City centre, Umeå city and Umeå Municipality. An illustration of how these areas relate to each other can be seen in Figure 7. A and B represent the two parts of the city, University area and City centre, that are districts in Umeå city, C which in turn is a part of the Umeå municipality, D.

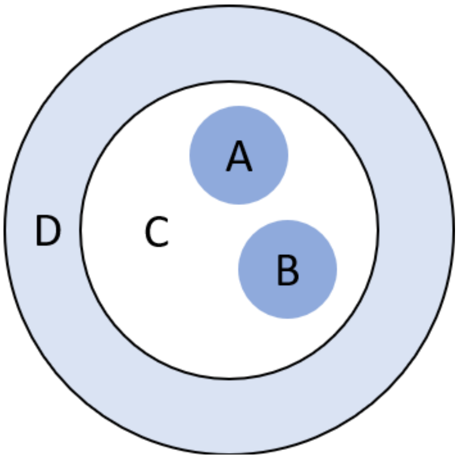

Figure 7. Illustration of the different geographical areas defined in the scenarios, A = City centre, B = University area, C = Umeå City, D = Umeå Municipality.

To illustrate how the upscaling potential is evaluated, solution U2 is used as an example. In the scenario it has been estimated that U2 has physical presence in 75% of the University area, 50% of City centre and 25% of Umeå city and 0% of Umeå municipality. For the upscaling effects this is interpreted as that 75% of the buildings in A implements the solutions, 50% of the buildings in B and the 25% presence in C implies that 25% of the buildings in C, located in other parts than A and B implement the solution. No buildings outside of Umeå city, C implement the solution since the physical presence in Umeå municipality, D is estimated to 0%. In addition to this it is also assumed that not all building types are suitable for every solution. Therefore, the scenarios are interpreted in such a way that a physical presence of 50% in e.g. the city centre implies that 50% of the suitable buildings have implemented the solution.

As mentioned previously the scenarios are developed through a general assessment but to be able to evaluate the upscaling effects, more detailed data of the buildings in the different areas are gathered. In line with the division of district made by Umeå kommun the University area is assumed to include the area Liljan, the hospital area and the university area and the City centre is assumed to include centrum, väst på stan and öst på stan (Umeå kommun, 2019). Building data for these areas are found using Umekartan (Umeå kommun, 2018) and building statistics for Umeå city and Umeå municipality are found through SCB (SCB, 2017). The building categories of interest for implementation of the solutions accommodate businesses, residences or civic functions (school, university, hospital). Umekartan shows the building footprint but the buildings in the University area and City centre are assumed to have three floors on average which makes the building area three times larger. The areas of the different building categories in the different parts of the city is presented in Table 17.

Table 17. Building categories and their distribution in the different parts of Umeå, (Umeå kommun, 2019) (Umeå kommun, 2018) (SCB, 2017).

Part of the city	Building category	Area [m^2]
City centre	Business	450 474
	Residential buildings	608 298
	Civic functions	102 279
University area	Business	-
	Residential buildings	23 232
	Civic functions	456 505
Umeå city	Business	103 526
	Residential buildings	1 723 470
	Civic functions	331 216
Umeå municipality	Business	86 000
	Residential buildings	183 000
	Civic functions	62 000

3.2.2 Solution U2 – Peak load variation management and peak power control

The aim of the U2 solution is to use buildings as thermal energy storage for shifting of heat load to reduce the demand of peak power generation in the district heating energy system. The solution also includes monitoring and smart control of buildings which makes it possible to also reduce the energy demand of the buildings.

The demonstration of this solution has shown that an **energy demand reduction of 8-10 %** is possible to achieve in a building with monitoring and smart control installed. The demonstration also shows that it is possible to **shift approximately 50% of the heat load in a building for four hours** without affecting the indoor climate too much. The heat load can also be shifted to a lesser extent during longer time periods, e.g. 25% for eight hours.

This solution is mainly suitable for large buildings such as multi-family residential buildings and office buildings since the control system is quite expensive and the energy demand in these buildings is higher than in e.g. single-family houses. To be able to use a building as thermal energy storage it is favourable if the building structure is medium or heavy.

3.2.2.1 Umeå system analysis

The upscaling effects of this solution in Umeå is dependent on the existing heat demand of the buildings and this as well as the energy reduction potential for a residential and a non-residential building is presented in Table 18. According to the scenarios, U2 has physical **presence in 75% of the University area, 50% of City centre and 25% in the rest of Umeå city**. Since the U2 solution is not suitable for all types of buildings the scenario is interpreted in such a way that a physical presence of 75% in the university campus implies that 75% of the buildings in the suitable categories have implemented the solution.

Table 18. District heat demand for residential buildings (Energimyndigheten, 2018) and non-residential buildings (Energimyndigheten, 2018) with a possible reduction in energy demand due to smart control and monitoring.

	Residential buildings	Non-residential buildings
District heat demand [kWh/m^2]	131	123
Possible reduction	8%	8%
Yearly reduction in heat demand [kWh/m^2]	10.5	9.9
Upscaling potential [m^2]	752 441	742 691
Total reduction [GWh]	7.87	7.30

In this analysis, the energy reduction is assumed to be evenly distributed over the year, which means that the energy reduction in absolute numbers will vary over the year due to seasonal variations of the heat demand. The variation in heat demand is assumed to be the same as for the buildings modelled in U4, where the heat demand mainly varies with outdoor temperature and solar irradiation. Figure 8 illustrate the seasonal variation of the reduction in energy demand when it is upscaled according to the scenarios. **The total yearly energy reduction potential is 15.2 GWh** by implementing and upscaling this solution in Umeå.

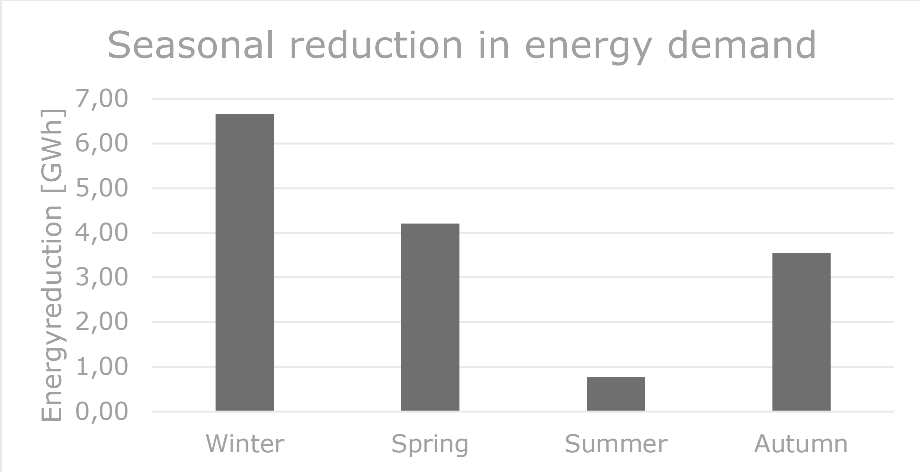

Figure 8. Seasonal reduction in energy demand with an upscaling of U2 solution in Umeå according to scenarios.

The other part of this solution, the heat load shifting is dependent on the thermal output in the building. The thermal output of buildings in Umeå is separated between new and old buildings, where older buildings has an average heat load of 70 W/m^2 and new buildings 40 W/m^2. Older buildings are here assumed to be built before year 2000. The possibility for shifting heat load is summarised in Table 19. As mentioned, it is possible to shift approximately half of the load for four hours and a smaller part for longer time, but the amount of energy shifted is the same.

Table 19. Potential to use buildings as thermal energy storage for shifting of heat load in Umeå.

	Old building (pre 2000)	New building
Thermal output [W/m^2]	70	40
Possible shifting	50% (25%)	50% (25%)
Time period [h]	4 (8)	4 (8)
Shifting of heat load [W/m^2]	35 (17.5)	20 (10)
Upscaling potential [m^2]	1 315 716	179 416
Load shift potential [MW]	46.1	3.6
Daily shifting of heat load [MWh]	184.2	14.4

The upscaling of this solution shows that it is **possible to shift 199 MWh heat load per day** in Umeå. This could be repeated several times, but it is important to remember that it is only possible to reduce the heat effect for a few hours with this method and the energy still needs to be supplied to the building to avoid poor comfort in the buildings.

The load shift potential with an upscaling of this solution is 50 MW for four hours or 25 MW for eight hours. This has been compared to the duration curve of the district heat production in 2019, to evaluate what potential the load shifting has on this scale. In the first quarter of 2019 it was not possible to operate one of the power plants on maximum capacity due to conversion to biooil in 2018. Nevertheless, it is assumed for the load shifting model that the maximum capacity of this plant was available, to evaluate the potential of load shifting for a whole year.

The two different load shifting possibilities has been compared, either 50 MW shifting for four hours or 25 MW for eight hours. The model evaluates every hour to find out if any of the oil fuelled plants are operated and the possibility to shift the load in time. **With load shifting for four hours it is possible to reduce the oil fuelled production to 3% of the level in 2019. With the eight-hour load shift it reduces the oil use to 27% of the use in 2019.** The duration curve of the oil fuelled generation before and with load shifting of four and eight hours respectively can be seen in Figure 9.

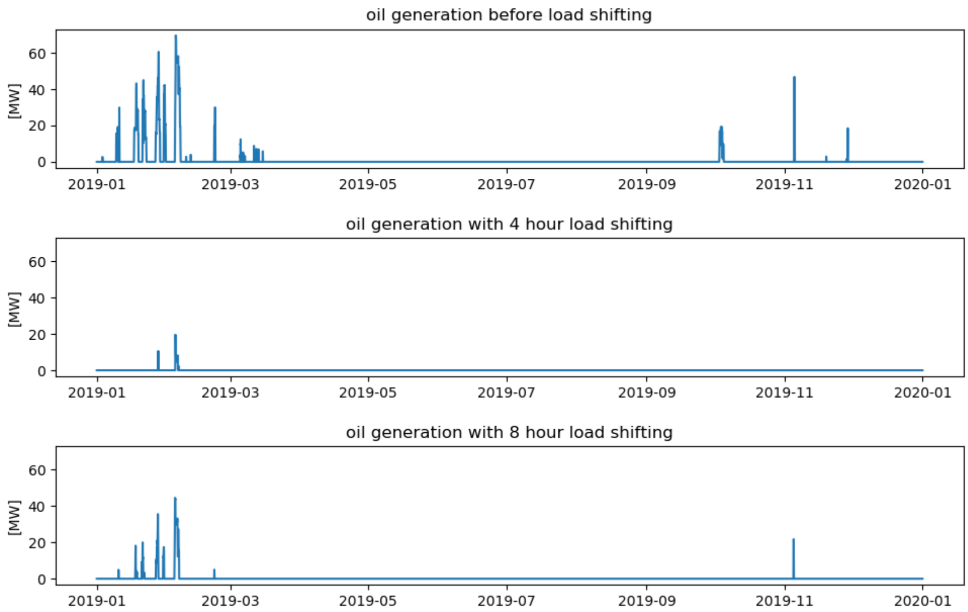

Figure 9. Oil fueled district heating generation without load shifting and with four and eight hours load shifting.

The model does not consider at which of the power plants the shifted load should be produced, only that there are available capacity and possible to generate with another unit. This evaluation does not consider limitations in the district heating grid itself which is one of the reasons why the oil fuelled plants is still used in Umeå. However, the peak heat demand does often occur within the city, where a large part of the buildings relevant for this solution is located. Therefore, it is probable that load shifting in these buildings would also mitigate the limitations in the grid itself.

3.2.2.2 Glasgow system analysis

The district heating system in Glasgow is much smaller than in Umeå which makes the upscaling effect of this solution in Glasgow less pronounced than in Umeå. The demand and possible reduction of heat demand in the buildings is presented in Table 20. The office buildings attached to the district heating system in Glasgow are mainly university buildings, where the majority are naturally ventilated open-plan buildings with a heating demand of 151 kWh/m^2 (Action Energy, 2003).

Table 20. Heat demand and possible energy reduction for the buildings connected to district heating in Glasgow.

	Residential buildings	**Office buildings**
District heat demand [kWh/m^2]	146	151
Possible reduction	8%	8%
Yearly reduction in heat demand [kWh/m^2]	11.7	12.1
Upscaling potential [m^2]	10 920	230 000
Total reduction [GWh]	0.13	2.78

The seasonal distribution of the upscaling potential of the U2 solution in Glasgow is presented in Figure 10. The yearly reduction in energy demand is assumed to be evenly distributed over the year and since the energy demand in absolute values is largest during wintertime, the energy reduction in absolute values is largest then. **The total yearly energy reduction potential is 2.9 GWh by implementing and upscaling this solution in Glasgow.**

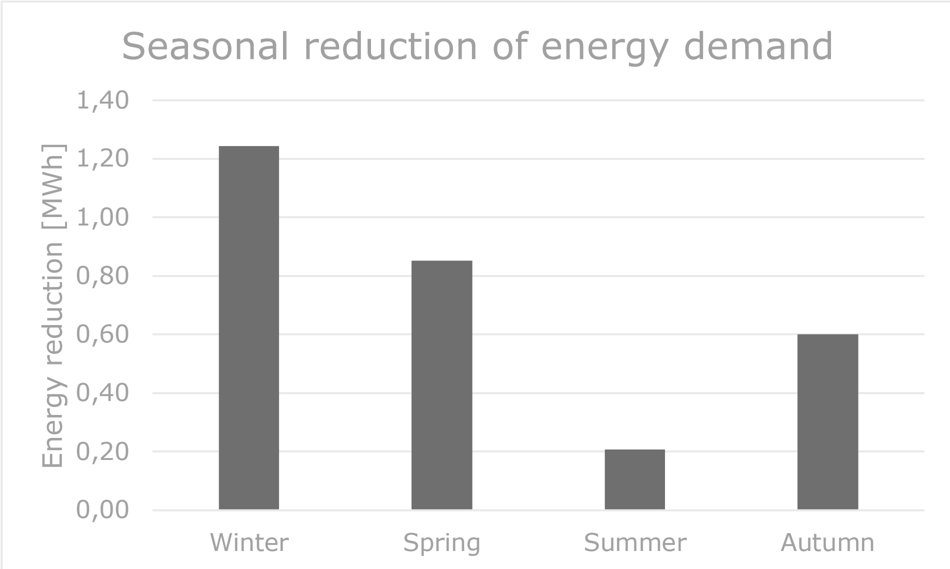

Figure 10. Seasonal distribution of the energy reduction potential in Glasgow.

The other part of this solution, the heat load shifting is dependent on the thermal output in the building. The thermal output of buildings in Glasgow and the possibility for shifting heat load is summarised in Table 21. It is assumed that the thermal output of both residential and university buildings connected to the district heating network is the same. As mentioned, it is possible to shift approximately half of the load for 4 hours and a smaller part for longer time, but the amount of energy shifted is the same.

Table 21. Potential to use buildings as thermal energy storage for shifting of heat load in Glasgow.

	Residential and office buildings
Thermal output [W/m^2]	17.6
Possible shifting	50% (25%)
Time period [h]	4 (8)
Shifting of heat load [W/m^2]	8.8 (4.4)
Upscaling potential [m^2]	240 920
Load shift potential [MW]	2.13
Daily shifting of heat load [MWh]	8.5

It is **possible to shift 2.13 MW heat load** from a certain point in time to another when upscaling this to the district heated connected residential and university buildings in Glasgow. **The daily heat energy possible to shift is 8.5 MWh,** which still must be supplied to the building to avoid poor comfort in the buildings.

3.2.2.3 Rotterdam system analysis

The upscaling effects of this solution in Rotterdam is dependent on the existing heat demand of the buildings and this as well as the energy reduction potential for a residential and a non-residential building is presented in Table 22.

Table 22. Heat demand and possible energy reduction for the buildings connected to district heating in Rotterdam.

	Residential buildings	Office buildings (new)	Office buildings (old)
District heat demand [kWh/m^2]	113	83.6	96.7
Possible reduction	8%	8%	8%
Yearly reduction in heat demand [kWh/m^2]	9.04	6.7	7.7
Upscaling potential [m^2]	1 606 468	233 950	127 955
Total reduction [GWh]	14.52	1.57	0.99

The seasonal distribution of the upscaling potential of the U2 solution in Rotterdam is presented in Figure 11. The yearly reduction in energy demand is assumed to be evenly distributed over the year and since the energy demand in absolute values is largest during wintertime, the energy reduction in absolute values is largest then. **The total yearly energy reduction potential is 17.1 GWh by implementing and upscaling this solution in Rotterdam.**

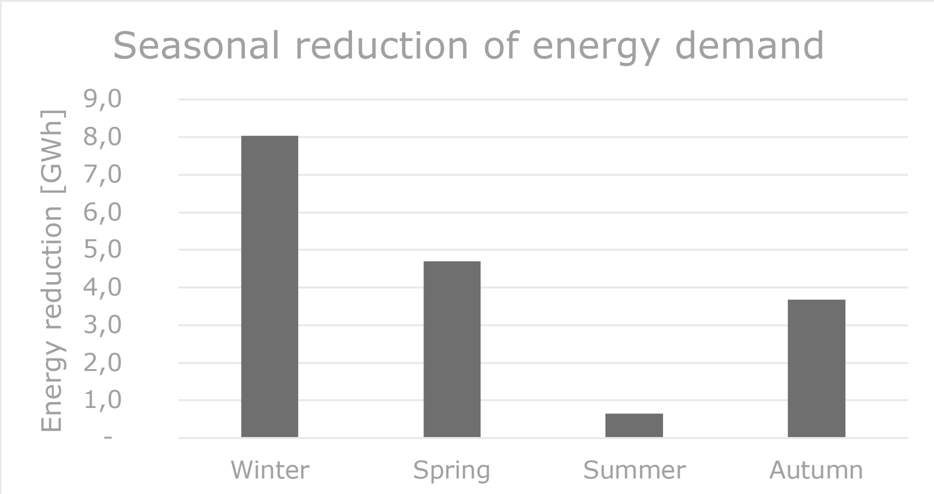

Figure 11. Seasonal distribution of the energy reduction potential in Rotterdam.

The other part of this solution, the heat load shifting is dependent on the thermal output in the building. The thermal output of buildings in Rotterdam and the possibility for shifting heat load is summarised in Table 23. As mentioned, it is possible to shift approximately half of the load for four hours and a smaller part for longer time, but the amount of energy shifted is the same.

Table 23. Potential to use buildings as thermal energy storage for shifting of heat load in Rotterdam.

	Residential building	**Office building (new)**	**Office building (old)**
Thermal output [W/m^2]	103	60	90
Possible shifting	50% (25%)	50% (25%)	50% (25%)
Time period [h]	4 (8)	4 (8)	4 (8)
Shifting of heat load [W/m^2]	51.5 (25.75)	30 (15)	42 (22.5)
Upscaling potential [m^2]	1 606 468	233 950	127 955
Load shift potential [MW]	82.7	7.0	5.8
Daily shifting of heat load [MWh]	330.9	28.1	23

It is **possible to shift 95.5 MW heat load** from a certain point in time to another when upscaling this to the district heated connected buildings in Rotterdam. **The daily heat energy possible to shift is 382 MWh**. This could be repeated several days but it is important to remember that it is only possible to reduce the heat effect for a few hours with this method and the energy still need to be supplied to the building to avoid poor comfort in the buildings.

3.2.2.4 Cost analysis

The U2 solution in Umeå has two different effects, it **both reduces the heating demand as well as it can be used to shift load and reduce peak power demand** in the heating system. **Different stakeholders might benefits from the two effects,** and there might not be any incentives for a building owner to implement this solution to reduce the peak power demand unless power tariffs are high enough to encourage a decrease in power demand, but if the measure reduces the cost of energy to a certain level it might be considered profitable also from a building owner perspective. According to our calculations the cost reduction with 2019 energy prices is 0.43 €/m^2 yearly, on average for residential and non-residential buildings. For an average multifamily house of 820 m^2 the possible savings with this solution is 360 €/year due to reduction in energy demand. **With the upscaling of the solution the total cost reduction is 640 400 €/year in Umeå**.

The cost effects for Umeå Energi to shift from oil to other fuels is not covered in this analysis since the model does not consider at which of the power plants the shifted load should be produced at, only that there are available capacity and possible to generate with other units instead. However, the oil generating units is the ones with the largest running costs and by reducing the use of them the production cost of the district heat will be reduced. By shifting as much as possible to the waste plant, the cost savings will increase since that has the lowest running cost.

The energy reduction potential of this solution results in a cost saving potential in Glasgow with 1.43 €/m^2 for the district heating connected buildings. With an average household size of 85 m^2 this result in a yearly saving per household of 120 €. **With an upscaling of the solution the saving potential is 35 090 € yearly, it can be noted that the upscaling potential in Glasgow is approximately 16% of the potential in Umeå**. For an average residential building of 820 m^2 the possible savings would be 1 156 € annually. The district heating system in Glasgow is limited and the production is based on natural gas CHP, which limits the cost savings potential of the district heating supplier due to peak load shifting in the district heating system.

The energy reduction potential of this solution results in a cost saving potential in Rotterdam with 0.72 €/m^2 for the district heating connected buildings on average. This is calculated with the energy prices for small consumers including 21% VAT as presented in Table 2 in section 2.2. **With an upscaling of the solution the saving potential is 1.56 M€ yearly, with an upscaling potential in Rotterdam that is 30% larger than in Umeå.** For an average residential building of 820 m^2 the possible savings would be 680 €/year. The district heating generation in Rotterdam is not evaluated and it is therefore not possible to estimate the cost saving potential of peak load shifting in buildings in Rotterdam.

3.2.2.5 Carbon effects

By upscaling the U2 solution to 1 630 buildings in **Umeå** connected to district heating, the energy saving potential of this solution can **reduce the CO_2 emissions with 730 tonnes** per year assuming average emissions for district heating in Umeå, presented in Table 3 in section 2.2.

The shifting of peak power due to this solution also has the potential of reducing CO_2 emissions since production is shifted from oil to other fuels. As mentioned in the description of the model in section 3.2.2.1. it is not considered at which power plant the shifted load is generated instead of the oil fuelled units. The emission from oil fuelled plants is calculated with the emission factor of 268.2 g/kWh (Gode, et al., 2011) whereas for the other generation the average emission factor for the district heating in Umeå 48.06 g/kWh presented in Table 3 is used. **The load shift of four hours has the potential to reduce the CO_2 emissions with almost 2 240 tonnes per year while the load shift of eight hours has the potential to reduce the emissions with 1 690 tonnes per year**. It should be noted that the sum of the emission reduction due to this solution with both load shifting and energy savings is not the sum of the two parts since they may overlap and affect each other.

The carbon intensity of the district heating in **Glasgow** is presented in Table 3 in section 2.2, 200 g/kWh, which results in a possible **carbon reduction of 582 tonnes/year** if this solution is upscaled. As stated in the cost analysis, the effects of peak load shifting will probably have limited effects on the CO_2 emissions as well, since the district heating production is mainly relying on gas.

The carbon intensity of the district heating in **Rotterdam** is presented in Table 3 in section 2.2, 81.2 g/kWh, which results in a possible **carbon reduction of 1 389 tonnes/year** if this solution is upscaled. The total CO_2 savings are larger in Rotterdam than Glasgow even if the carbon intensity of the district heating is lower in Rotterdam since the solution is scaled eight times more than in Glasgow. The CO_2 effects of peak load shifting in Rotterdam is not evaluated.

3.2.3 Solution U4 – Intelligent building control

The aim of the U4(b) solution is to reduce energy consumption in buildings by using **automatic control of ventilation, heating, cooling and lighting.** This is done by measuring presence, temperature and carbon dioxide in each room by a multi sensor.

To evaluate the effects of this solution a model was developed to calculate the energy consumption of a general office building in the lighthouse cities. The solution is also implemented in the model which makes it possible to compare the energy demand before and after the implementation. The model used to calculate the office load is based on the model presented by (Sandels, et al.,2015), and includes both electricity, cooling and heating consumption.

The model includes electricity consumption from lighting, computers, scanners, chargers as well as other appliances as fridges and coffee machines that are used within the office. Energy for ventilation, cooling and heating are also calculated. All values are calculated as specific energy use, yearly energy use per square meter. The area includes both office space as well as corridors, meeting rooms and bathrooms etc. An average office building is assumed to be 3200 m^2 (Energimyndigheten, 2007). Each employee is assumed to have 20 m^2 (Sveby, 2013). A 70 % occupancy of the office is assumed during weekdays and working hours, 8-17 (Sveby, 2013).

The building is assumed to be provided with a constant air volume (CAV) flow system with an air flow of 1.5 l/s per m^2. The ventilation system includes an air handling unit with a heat exchanger, which is the most common in the office buildings evaluated by (Energimyndigheten, 2007). The temperature efficiency of the heat exchanger is assumed to be 65%. The inlet air from the ventilation system to the building is assumed to be kept constant at 19°C, which requires pre-heating and cooling of the air, dependent on the outside temperature. The energy consumption is calculated with the assumption that the indoor temperature is kept between 21-23°C. The building is assumed to have a thermal capacitance of 60 kWh/°C.

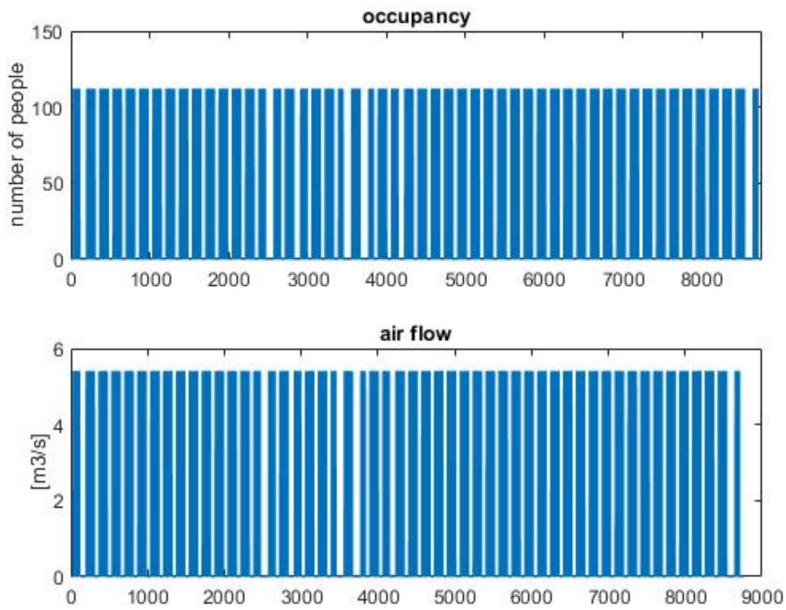

Figure 12. Occupancy level and air flow in the ventilation system throughout the year.

3.2.3.1 Model implementation of smart building control

The model has been adapted to represent the implementation of the smart control equipment that is demonstrated in one of the University buildings in Umeå which makes it possible to control lighting and indoor climate through the ventilation and heating and cooling systems.

The smart control equipment turns off the light when no occupancy is detected in the room. The air flow is also regulated with respect to occupancy in the room, with two levels of air flow during 7-19 at workdays. It is assumed that the air flow is zero outside of these hours. The heating and cooling systems is regulated to keep the temperature within 21-23 °C. It is still assumed in the model that the occupancy level is 70% during workhours throughout the year and the model does not capture seasonal and daily variations due to vacations and movement of people within the building which makes some offices empty during meetings for example. Therefore, it is likely that the energy reduction of this solution is even larger than captured with this model. The model is adapted to each lighthouse city by using climate data and U-values for each city. The data and results for each city is presented separately in the coming sections.

3.2.3.2 Umeå system analysis

The transmission factors of the building envelope used for the buildings in Umeå are presented in Table 24.

Table 24. Transmission factors used for the building envelopes in Umeå (Sveby, 2013).

	U_{roof}	U_{ground}	U_{window}	U_{wall}
[W/m²K]	0.19	0.32	1.2	0.32

The climate data used as input to the model is normalised data for the year 2017 in Umeå, developed by (Sveby, 2019). The outside temperature and the solar radiation are presented in Figure 13. The mean temperature in Umeå is 4.0 °C and the mean solar radiation is 92.0 W/m^2.

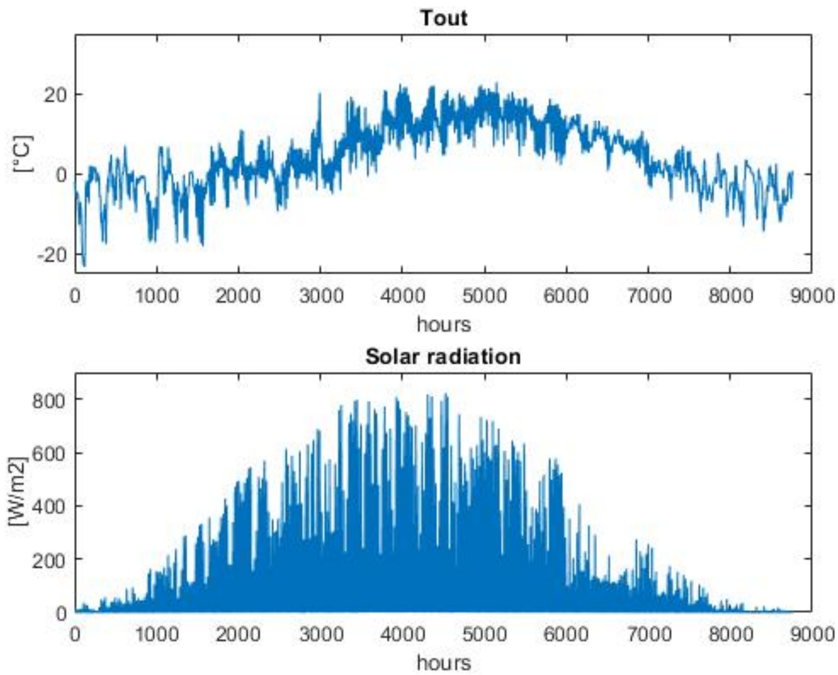

Figure 13. Temperature and solar radiation in Umeå with hourly resolution (Sveby, 2019).

The energy demand of a modelled office in Umeå can be seen in Figure 14. The total heating, cooling and electricity demand is shown as well as the different appliances which adds up to the total electricity demand.

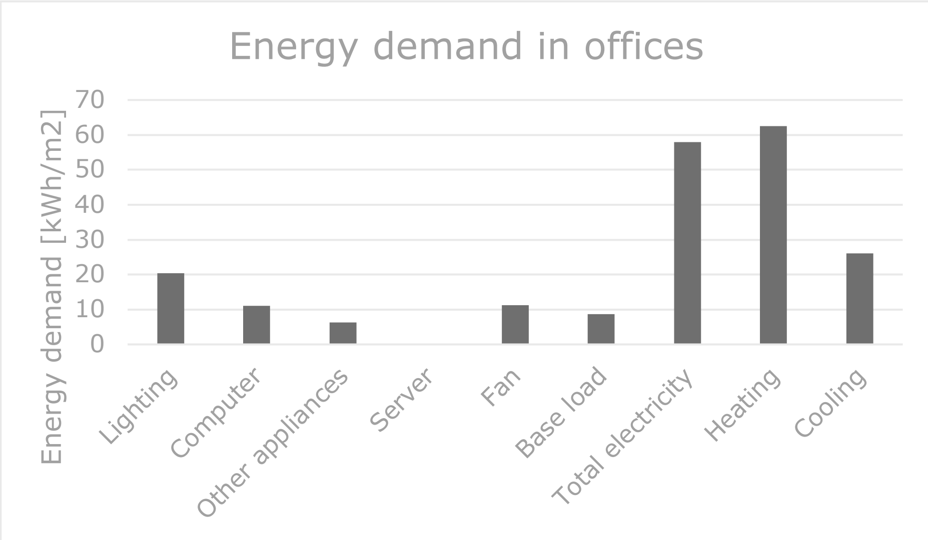

Figure 14. Energy demand of a modelled office in Umeå, before the smart control equipment is implemented.

The distribution of the energy demand between the four seasons is presented in Figure 15. The heating and cooling demand vary throughout the year, while the electricity demand is almost constant throughout the year. It is mainly the occupancy that affect the electricity consumption and it is assumed to be constant during workhours in this model.

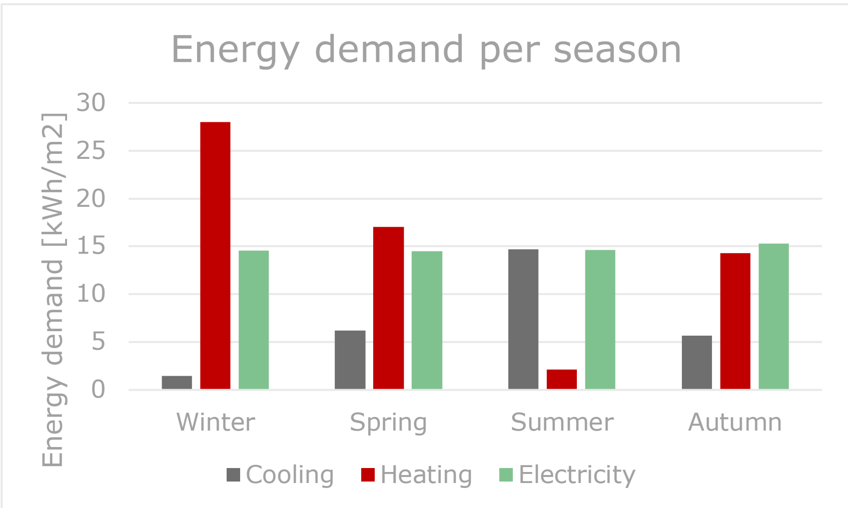

Figure 15. The distribution of energy demand per m^2 for the different seasons.

Table 25 summarises the results, both before and after the implementation of the smart control equipment in the office buildings as well as the difference. A negative difference represents a reduction in energy demand after the implementation and a positive difference represent an increase in energy demand after the implementation. As can be seen, the heating demand increases when the solution is implemented. This is due to the reduction in electricity demand since the lighting control reduce heat emitted by the lighting. **The total energy demand per m^2 is reduced by 16%.**

Table 25. Comparison of energy demand for office building in Umeå before and after implementation of smart control equipment.

	Baseline	Smart control equipment	Difference
Cooling [kWh/m^2]	26.15	15.89	-39%
Heating [kWh/m^2]	62.47	63.42	2%
Electricity [kWh/m^2]	57.91	43.29	-25%
Total [kWh/m^2]	146.5	122.6	-16%

The U4 solution is assumed to have physical presence of 75% of the buildings in all parts of the city, according to the scenarios. It is not implemented in residential buildings since the sensors and equipment is quite expensive. Therefore, it is diffused to 75% to buildings with business functions. Nevertheless, the demonstrations of the U4 solution in Umeå is taking part in the university, which is buildings classified as civic functions. Therefore, it is assumed that also 50% of the buildings with civic functions has the possibility to implement a solution like this. **This result in an upscaling to 956 000 m^2. The upscaling potential of this solutions is an energy reduction of 23 GWh/year in Umeå,** and the numbers are presented in Table 26.

Table 26. Energy reduction potential when upscaling the U4 solution in Umeå.

	Heating	Cooling	Electricity	Total
GWh/year	0.91	- 9.81	-13.98	- 22.88

The energy demand reduction on a seasonal level due to upscaling of U4 solution is presented in Figure 16. The maximum demand reduction can be seen in the summer while the lowest reduction can be seen during winter. Winter is the only season when the heating demand is reduced, the other months it increases.

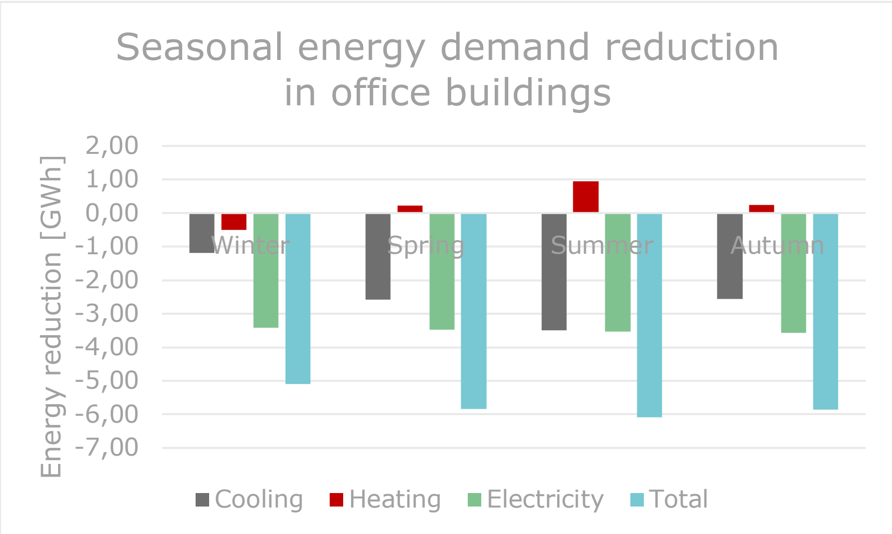

Figure 16. Seasonal distribution of energy demand reduction with smart control equipment implemented and upscaled in office buildings in Umeå.

3.2.3.3 Glasgow system analysis

The building stock in Glasgow consists of buildings in different categories with large fluctuations in U-values. The U4 solutions requires some basic conditions for the buildings, such as mechanical supply and exhaust ventilations, pressure-controlled ventilation units with heat recovery as well as heating and cooling system. Since it is only relatively new building in Glasgow that fulfils this requirement, U-values representing these buildings has been used in this model and are presented in Table 27.

Table 27. Transmission factors used for the building envelopes in Glasgow, representing 10% of the office buildings that fulfils the requirement of this solution (Jenkins, Banfill, & Pelligrini-Masini), (Scottish Government, 2017), (Scottish Government, 2018).

	U_{roof}	U_{ground}	U_{window}	U_{wall}
[W/m^{2}K]	0.2	0.22	2.75	0.44

The outside temperature and the solar radiation for Glasgow used as input to the model can be seen in Figure 53 in chapter 6 Appendix – Figures. The mean temperature of Glasgow is 9.3 °C and the mean solar radiation is 62.3 W/m^2.

The energy demand for an office building located in Glasgow is calculated with the same assumptions as for the office in Umeå but with climate data and U-values for buildings in

Glasgow as input. The results are presented in Table 28. As can be seen, the reduction of cooling demand is 40% and the heating demand increases with 12% while the total energy demand reduces with 19%, which is 23.17 kWh/m^2 in absolute values.

Table 28. Comparison of energy demand for office building in Glasgow before and after implementation of smart control equipment.

	Before	Smart control equipment	Difference
Cooling [kWh/m^2]	31.02	18.76	-40%
Heating [kWh/m^2]	31.81	35.52	12%
Electricity [kWh/m^2]	58.18	43.55	-25%
Total [kWh/m^2]	121	97.83	-19%

The overall office space floor area in Glasgow city centre is 1 006 011 m^2 and 10% of these are estimated to be modern buildings with the possibility to implement this solution. The potential energy reduction of upscaling U4 solution to this office area is presented in Table 29. The heating demand increases when the solution is implemented while the demand for cooling and electricity is reduced. The total energy demand for offices in Glasgow city centre is reduced by 2.33 GWh/year.

Table 29. Energy reduction potential when upscaling the U4 solution in Glasgow.

	Heating	Cooling	Electricity	Total
GWh/year	0.37	- 1.23	-1.47	- 2.33

The seasonal distribution of the energy reduction due to upscaling of U4 in Glasgow is presented in Figure 17. The maximum reduction occurs during summer when the cooling and electricity demands decrease, while the heating demand increases a bit.

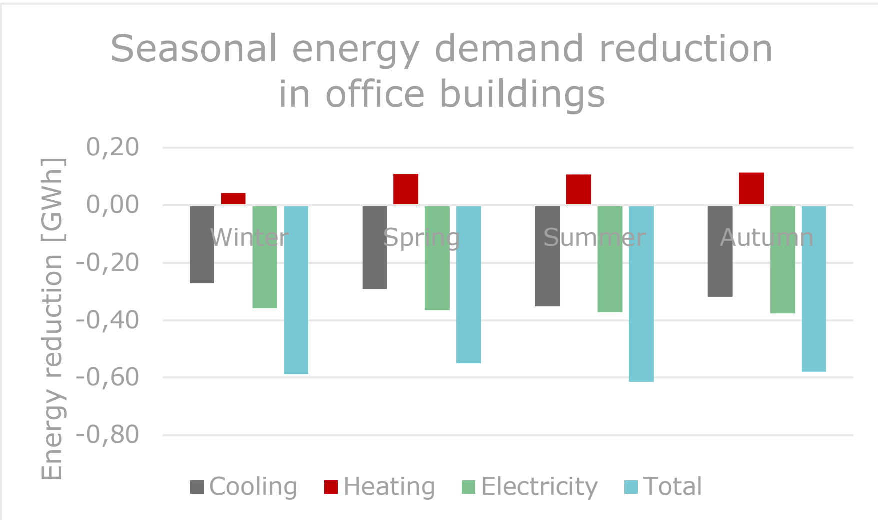

Figure 17. Seasonal distribution of energy demand reduction with smart control equipment implemented and upscaled in office buildings in Glasgow.

3.2.3.4 Rotterdam system analysis

The transmission factors of the building envelope used for the buildings in Rotterdam are presented in Table 30.

Table 30. Transmission factors used for the building envelopes in Rotterdam (Sveby, 2013).

	U_{roof}	U_{ground}	U_{window}	U_{wall}
[W/m^{2}K]	0.19	0.32	1.2	0.32

The outside temperature and the solar radiation for Rotterdam used as input to the model is presented in Figure 54 in chapter 6 Appendix – Figures, The mean temperature of Rotterdam is 10.0 °C and the mean solar radiation is 112.2 W/m^2.

The energy demand for an office building located in Rotterdam is calculated with the same assumptions as for the office in Umeå but with climate data for Rotterdam as input. The results are presented in Table 31 where it can be seen that the reduction of cooling demand is 35% and the heating demand increases with 9%. **The total energy reduction is 20%.**

Table 31. Comparison of energy demand for office building in Rotterdam before and after implementation of smart control equipment.

	Before	Smart control equipment	Difference
Cooling [kWh/m^2]	40.79	26.71	-35%
Heating [kWh/m^2]	29.21	31.81	9%
Electricity [kWh/m^2]	57.63	43.01	-25%
Total [kWh/m^2]	127.63	101.53	-20%

The scaling potential of this solution is assumed to be 723 810 m^2, which is 20% of the total office floor area in Rotterdam. The potential energy reduction of upscaling U4 solution to this office area is presented in Table 32.

Table 32. Energy reduction potential when implementing and upscaling U4 solution to the office floor area in Rotterdam.

	Heating	Cooling	Electricity	Total
GWh/year	1.88	- 10.19	- 10.58	- 18.89

The seasonal distribution of the energy demand with the smart control equipment implemented and upscaled to in Rotterdam is presented in Figure 18.

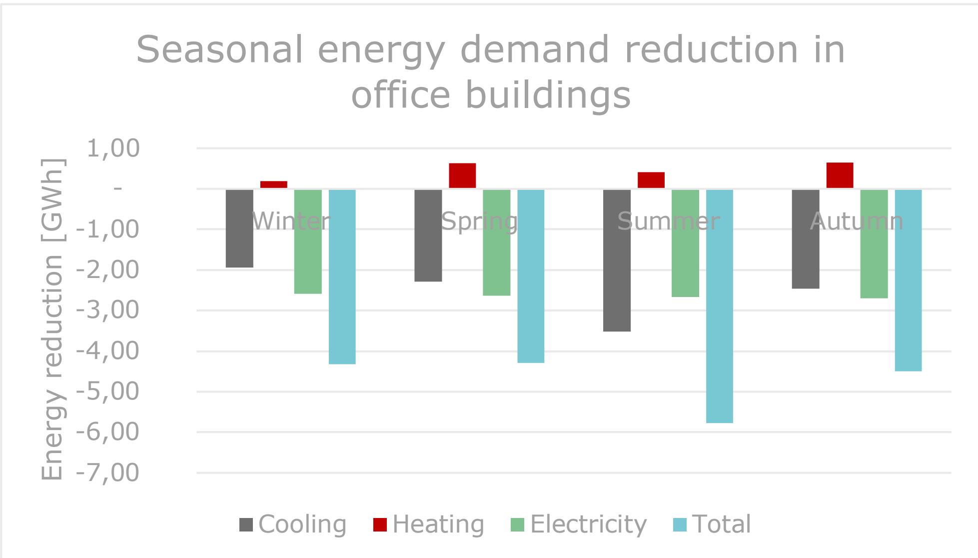

Figure 18. Seasonal distribution of energy demand reduction with smart control equipment implemented and upscaled in office buildings in Rotterdam.

3.2.3.5 Cost Analysis

The intelligent building control, U4, can aid building owners to lower the energy use in the buildings and reduce the cost for energy by optimising the use of the equipment. The cooling demand is assumed to be covered by a cooling machine with a COP of 2.7 (Energimyndigheten, 2007). According to the calculations the cost reduction for an office building of 900 m^2 would be 1 420 €/year. **If upscaled to all buildings, it has the potential of reducing the cost for energy with 1.505 M€ per year.**

This solution upscaled in **Glasgow has the potential to reduce the cost of energy by 0.477 M€ yearly**, if implemented in gas heated buildings with cooling supplied by cooling machines with a COP of 2.7. To compare it with Umeå, an office building of 900 m^2 in Glasgow will save approximately 4 260 € by implementing this solution. That is **three times the saving potential compared to when implemented in Umeå. This is due to the higher electricity price in the UK,** which makes the cost savings from an energy reduction measure, including electricity, larger in the UK than in Sweden.

This solution has the potential of **reducing the cost of energy for small consumers with 3.406 M€ if upscaled in Rotterdam** in gas heated buildings with cooling supplied by cooling machines with a COP of 2.7. In relation to the other cities, an office building of 900 m^2 in Rotterdam will save 4 230 € which is almost three times as much as the saving potential in Umeå. The energy savings per m^2 differs a bit between the three cities but the main difference in cost savings potential is related to the difference in energy prices. **With higher electricity prices as in Glasgow and Rotterdam, this solution has a larger potential of reducing the energy bill.**

3.2.3.6 Carbon Effects

The energy reduction achieved through upscaling of the intelligent building control, U4, can reduce the **CO_2 emissions by 840 tonnes per year in Umeå** if the cooling is supplied by a cooling machine with a COP of 2.7 and the Nordic electricity mix is considered. For a building of 900 m^2 this leads to reduction of carbon emissions of 790 kg per year.

The possible **CO_2 emission reduction** when upscaling this solution in **Glasgow is 456 tonnes per year**. Compared to Umeå the upscaling potential in Glasgow is only around 10% of that in Umeå, which makes **the emission savings per area more extensive in Glasgow than in Umeå**. As a comparison, a similar building of 900 m^2 in Glasgow, reduced the carbon emissions due to energy savings with 4.08 tonnes per year.

The possible **CO_2 emissions reduction** of this solution when upscaled in **Rotterdam is 5 690 tonnes per year.** This is with an upscaling potential that is only around 75% of the potential in Umeå. A 900 m^2 building in Rotterdam will reduce the CO_2 emissions with 7.08 tonnes yearly. This is both due to the difference in energy reduction of the solution when implemented in the three cities, but the main reason for the larger carbon savings in both Glasgow and Rotterdam compared to Umeå is due to the higher carbon intensity in the energy generation in Rotterdam and Glasgow compared Umeå. **The carbon intensity in Umeå of both district heating and electricity generation is around 10% of the carbon intensity in Rotterdam**.

3.2.4 Solution U9 – Demand Side Management

This solution reduces the energy demand in buildings by optimising the use of them. Sensors gather data such as human presence, temperature and CO_2 to predict and manage behaviours as well as services in the buildings. One example of this is to relocate people to use the same floor in the building if there are low occupancy, to reduce the demand for e.g. ventilation and electricity at other floors in the building. The demonstration of U9 is used as a complement to U2 and U4 at the University in Umeå.

The energy saving potential of this solution is estimated to 7%, based on energy use and attendance. This solution will likely result in even larger saving potentials in building blocks where there are possibilities to reduce the energy demand in whole buildings during time periods with relocation of people.

3.2.4.1 Umeå system analysis

The absolute energy savings and the effects on the energy system of this solution is dependent on the energy demand in the building before the solution is implemented as well as the size of the upscaling. According to the scenarios, the U9 solution is assumed to have physical presence of 75% of the buildings in the University area, 25% in the City centre, 25% in Umeå city and 0% in Umeå municipality. **This results in yearly energy savings of 7.1 GWh in Umeå.** A summary of the values used for the calculations is presented in Table 33. It is assumed that 75% of the total energy saving potential is related to electricity and the other 25% to heat.

Table 33. Specifications of U9 solution in Umeå, with energy demand of non-residential buildings which is the sum of heat demand (Energimyndigheten, 2018) and electricity demand (Energimyndigheten, 2007).

	Non-residential buildings
Energy demand [kWh/m^2]	221
Yearly reduction potential	7%
Reduction in energy demand [kWh/m^2]	15.47
Upscaling potential [m^2]	604 503
Yearly energy reduction [GWh]	7.1

3.2.4.2 Glasgow system analysis

The U9 solution is assumed to be applicable to **10% of the office floor area** in the city centre. By implementing and upscaling the solution in Glasgow it has the potential to **reduce the energy demand with 1.2 GWh yearly.** Table 34 summarizes the values used for this calculation. It is assumed that 75% of the total energy saving potential is related to electricity and the other 25% to heat.

Table 34. Specifications of U9 solution in Glasgow.

	Office buildings
Energy demand [kWh/m^2]	168
Yearly reduction potential	7%
Reduction in energy demand [kWh/m^2]	11.8
Upscaling potential [m^2]	100 601
Yearly energy reduction [GWh]	1.2

3.2.4.3 Rotterdam system analysis

The U9 solution is assumed to be applicable to **30% of the total office buildings area**, since those are large buildings where it might be possible to implement demand side management and relocate peopled with respect to occupancy. An implementation and upscaling of the U9 solution in Rotterdam has the potential to **reduce the energy demand with 14 GWh yearly**. Table 35 summarizes the values used for this calculation. It is assumed that 75% of the total energy saving potential is related to electricity and the rest 25% to heat.

Table 35. Specifications of U9 solution in Rotterdam.

	Office buildings (after 1976)	Office buildings (before 1976)
Energy demand [kWh/m^2]	183.3	184.9
Yearly reduction potential	7%	7%
Reduction in energy demand [kWh/m^2]	12.8	12.9
Upscaling potential [m^2]	383 866	701 849
Yearly energy reduction [GWh]	5	9

3.2.4.4 Cost Analysis

The energy reduction due to the U9 solution, demand side management, is assumed to mainly be applicable in large buildings and for a building of around 1000 m^2 it is possible to save 566 €/year. With the upscaling potential in **Umeå, it reduces energy costs with 0.342 M€ per year.**

By implementing and upscaling this solution in **Glasgow** it is possible to **save 0.243 M€ yearly**. For a building of 1000 m^2 this result in cost savings of 2 420 € per year, which is around four times the cost saving for a similar building in Umeå.

With an upscaling of this solution in **Rotterdam** it is possible to **save 2.966 M€ per year**. For a building of 1000 m^2 it equals a cost saving of 2 730 € per year. This is **around 50% larger cost savings than in Glasgow and almost five times the cost savings for a building at the same size in Umeå.**

3.2.4.5 Carbon effects

The carbon emission effects of upscaling demand side management in **Umeå is a reduction of 350 tonnes/year**. As mentioned above, this is with the assumption that 75% of the energy saving is electricity savings and 25% is heat savings. For a building of 1000 m^2 this reduce the carbon emissions by 580 kg per year due to lower energy consumption.

With an upscaling of this solution in **Glasgow it reduces 312 tonnes CO_2 per year**, if implemented in gas heated buildings. For a building of 1000 m^2 this reduce the carbon emissions by 3.10 tonnes per year due to lower energy consumption.

With an upscaling of this solution in **Rotterdam it reduces 5 410 tonnes CO_2 per year**, if implemented in gas heated buildings. For a building of 1000 m^2 this reduce the carbon emissions by 4.98 tonnes per year due to lower energy consumption.

3.3 Glasgow solutions

The solutions in Glasgow are highly interconnected and therefore hard to present one by one. The ones included in this analysis is:

- G2, G4 & G5 – EV charging hub battery storage and optimization of the integration of near-site RES
- G2 & G9 – Battery-supported load management in high-rise flats

The energy prices used in the cost calculations in Glasgow is presented in Table 2 in section 2.2 where the Glasgow prices represent the market prices of today. The CO_2 emission factors used to calculate the carbon savings is presented in Table 3 in section 2.2.

3.3.1 Upscaling of solutions in Glasgow

The upscaling of solutions reported here looks at the impact of rolling out the Glasgow smart street solutions city-wide. Note that in the case of the EV charging hub solution, the roll out is only to car park facilities linked to Glasgow City Council, consequently the estimate of energy and carbon savings is less than would be the case if the solution was rolled out to all car parks across Glasgow.

3.3.2 Solution G2, G4 and G5

The aims of this work are firstly to **quantify the performance of the PV canopy system** in each of the three cities and secondly to **determine how many electric vehicles such a system could suppor**t. The results are presented in terms of energy or vehicles per 100m^2 of PV so that they can be simply scaled to assess different penetration levels of the solution in each city.

It should be noted that the analysis presented here makes the assumption that all of the energy converted by the PV is used to charge electric vehicles. In reality this would require a substantial battery storage system, since the PV production and charging may take place during different times. More detailed analysis of a battery storage deployed in conjunction with the Glasgow system is described by (Allison & Kelly, 2018).

3.3.2.1 Modelling work

The modelling work described here was initially undertaken for Work Package 4 of RUGGEDISED Task 4.2: *Increase the energy efficiency at the district level*. Specifically, the work contributed to the development of Glasgow smart solutions G2: *Deployment of a suitable battery storage technology in the project district; G4: Optimisation of the integration of near-site RES* and G5: *EV Charging hub in city centre car park*. The Glasgow car park charging system is described in more detail by (Hand & Kelly, 2017). Briefly, the basic system comprises a PV array with a nominal peak capacity of 200 kW_p, corresponding to approximately 1250 m^2 of PV panels, situated on the roof of the car park, tilted at 20° to the horizontal. A full building simulation model of the array, car park and surrounding area had been developed for the ESP-r building simulation tool (Clarke, 2001). This is shown in Figure 19.

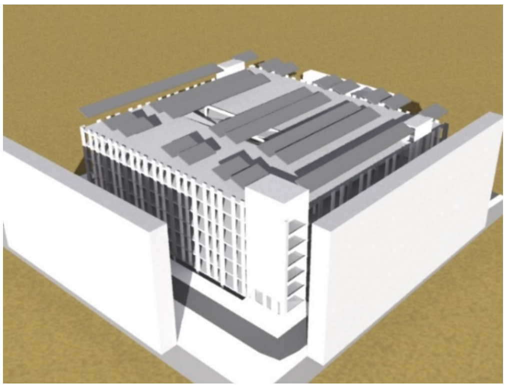

Figure 19: ESP-r model of the Duke St. Car Park

ESP-r is a long-established building simulation tool that explicitly computes the transient energy and mass transfer processes in a building over a user-defined time interval (e.g. a day, a year, etc.). An ESP-r model comprises a 3-D building geometry, coupled with explicit details of constructions, conventional and renewable energy systems, and control requirements. The technical basis of ESP-r is described in detail by Clarke (2001). ESP-r has been extensively validated and many of these validation efforts are summarised by (Strachan, Kokogiannakis, & Macdonald, 2008).

ESP-r has an in-built electrical solver (Kelly, 1998) that allows the output from building integrated renewables such as PV to be calculated according to time-varying climate conditions. The solver can also be used to model power flows in electrical networks within and external to buildings.

3.3.2.2 Glasgow System Analysis

Simulating the car park model with typical Glasgow climate data indicated that the annual PV electrical generation was approximately 122 000 kWh, and **average annual energy yield per 100 m^2 of 9 760 kWh** (Hand & Kelly, 2017). The modelled output of the array is shown in Figure 20, which shows the hour-by-hour variation in power.

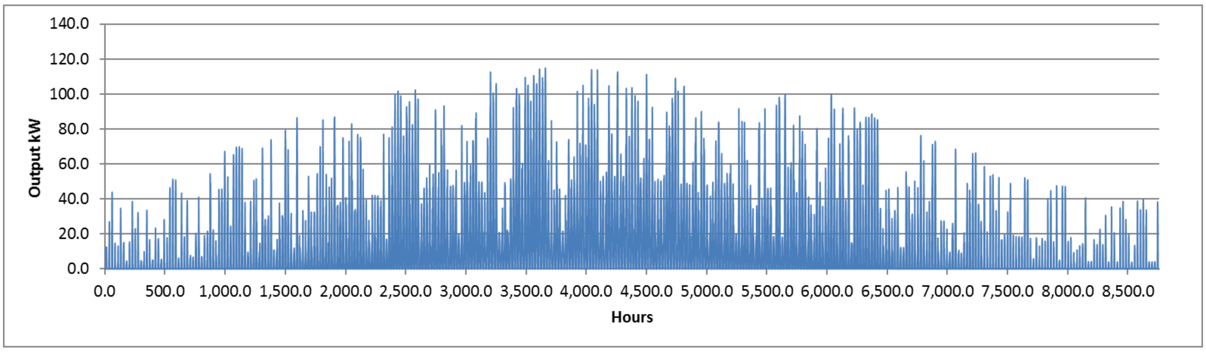

Figure 20: simulated PV electrical output.

Figure 21 gives an indication of the seasonal variation in the PV generation, with the output of the array summed over each of the four seasons and normalised per 100 m^2 of array area.

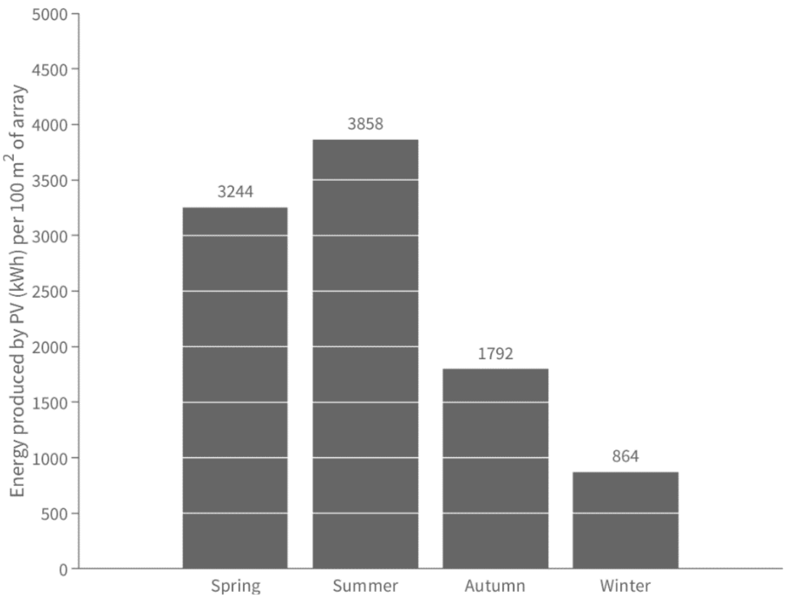

Figure 21: Energy yield from Glasgow PV per season per 100m².

The bulk of the electricity produced is in spring and summer, with little produced in Autumn or Winter due to weaker solar radiation and cloudier conditions.

Assuming the PV output power was attached to an ideally sized and controlled battery, such that all of the generation could be captured; then dividing the annual energy yield by the useable battery capacity of different electric vehicle types gives an indication of the number of complete charges per vehicle make and model that could be supported by the car park PV array.

The top 15 Ultra Low Emission Vehicles (ULEVs)[1] licensed in the UK is given in Figure 22 alongside their useable battery capacity. These represent approx. 81% of the licensed ULEVs on the road. The figure below shows the number of different electric vehicle types and their battery capacity.

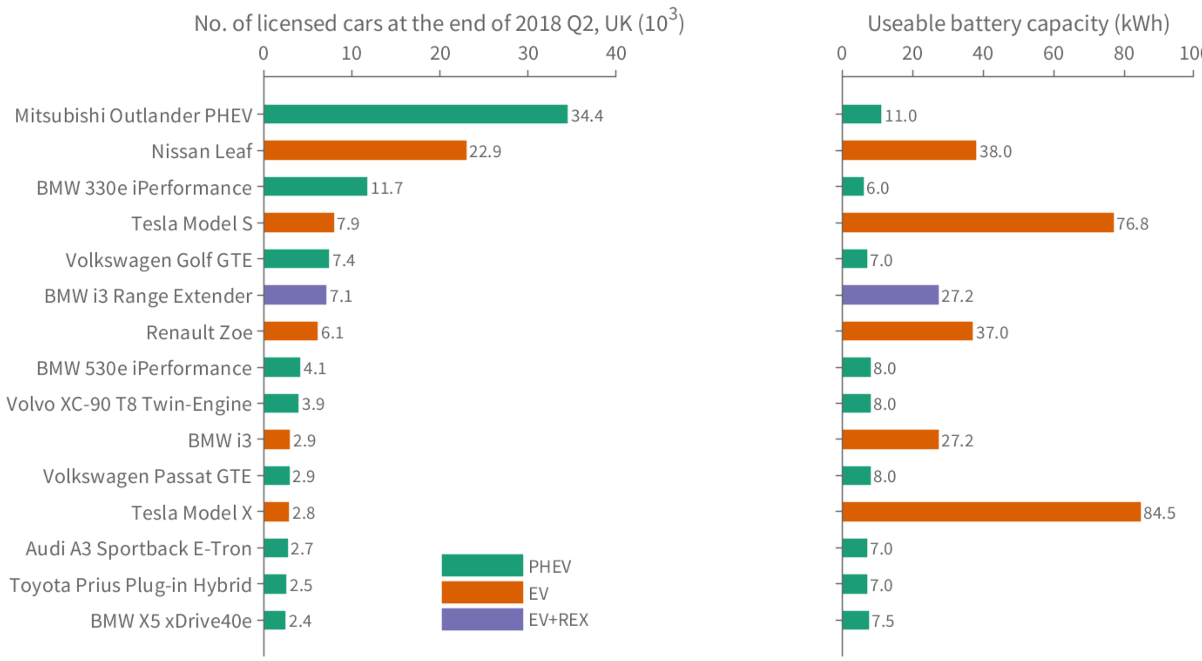

Figure 22: Top 15 ULEV licensed cars at the end of 2018 Q2 by make and model, UK (Department for Transport statistics, DVLA/DfT, 2018).

[1] ULEVs are vehicles with fully electric power and cars and vans with tail pipe emissions below 75 g/km.

The number of complete charges for specific vehicle types that could be supported annually per 100 m^2 of array are shown in Figure 23 below.

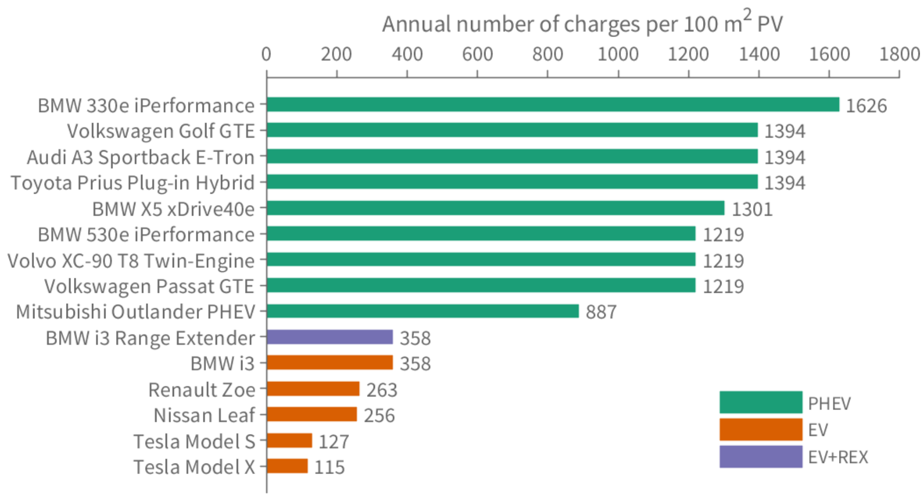

Figure 23: Number of complete charges per vehicle make & model.

A more generic performance metric is provided by the basic vehicle type. For electric vehicle, these are assumed to be: plug-in hybrid electric vehicle (PHEV), electric vehicle (EV) and electric vehicle with range extension (EV + REX). The number of complete charges per basic vehicle type can be ascertained using the weighted arithmetic mean[2] battery capacity:

$$\begin{aligned} \overline{E}_{\mathbf{EV}} &= \mathbf{47.4\,kWh} \\ \overline{E}_{\mathbf{EV+REX}} &= \mathbf{27.2\,kWh} \\ \overline{E}_{\mathbf{PHEV}} &= \mathbf{8.9\,kWh} \end{aligned}$$

Using these weighted means and the computed PV generation for Glasgow, the number of complete charges per vehicle type per year per 100 m^2 of PV is given in Figure 24.

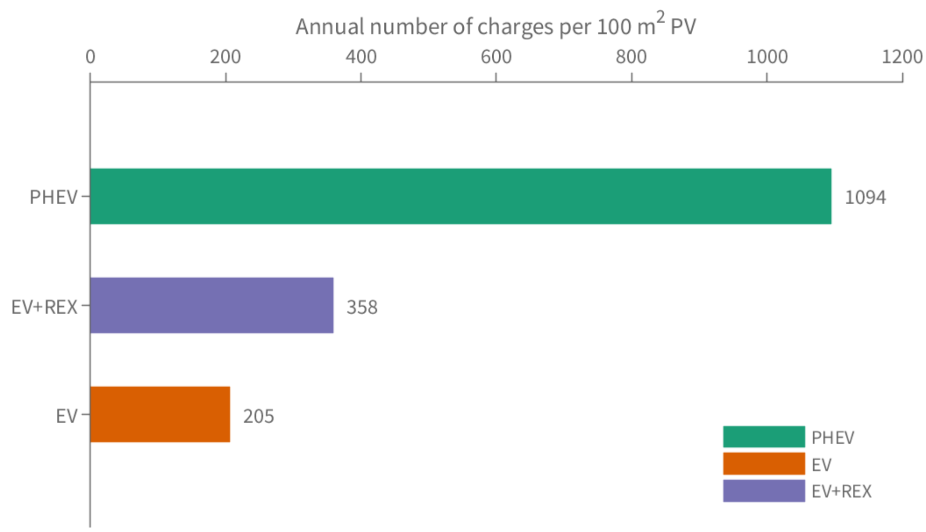

Figure 24: Number of complete charges per vehicle type per 100m^2 of PV.

[2] The weighted mean of a non-empty set of data $\{x_1, x_2, \ldots, x_n\}$ with non-negative weights $\{w_1, w_2, \ldots, w_n\}$ is given by $\bar{x} = \frac{\sum_{i=1}^{n} w_i x_i}{\sum_{i=1}^{n} w_i}$. The weights are equal to the number of licensed vehicles of that type and model on the road, $w_i = N_{veh,i}$. x_i being the specific number of a make and model.

The huge difference in the number of charges is linked to the difference in battery capacities of different vehicles. For examples, the Mitsubishi Outlander PHEV has a battery capacity of 11 kWh, whilst a Tesla Model S has a capacity of approximately 77 kWh.

Using the data in Figure 21, the number of complete charges for each vehicle type per season is shown in Figure 25. This again highlights the strong seasonal variability in Glasgow's solar irradiance, with significant resource in Spring and Summer and little in Autumn and Winter.

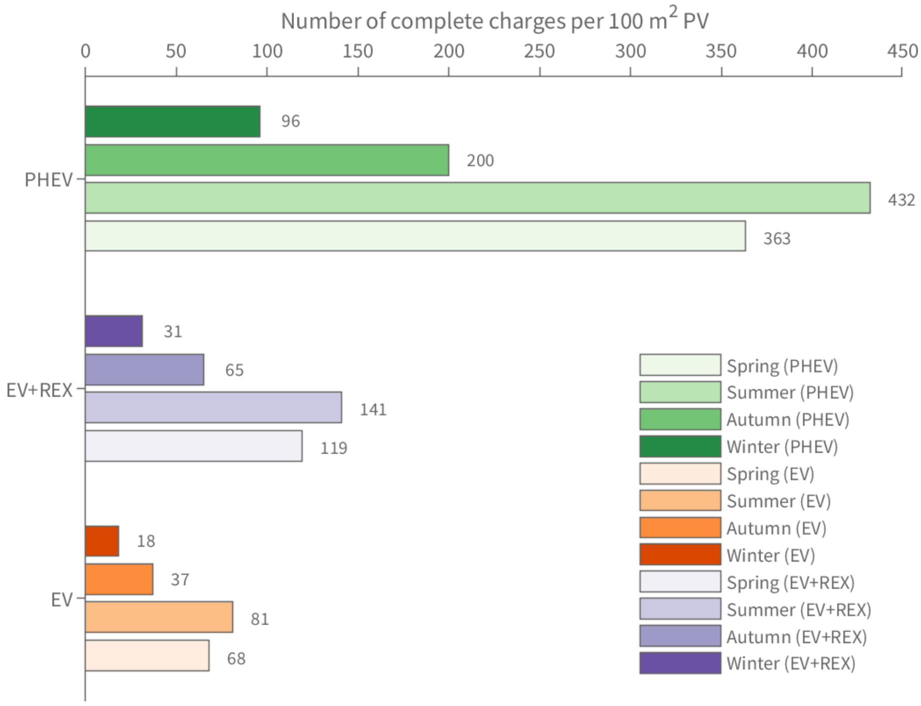

Figure 25: Number of complete charges per vehicle type per 100m^2 of PV in each season.

The possible area of PV that could be installed in **Glasgow is 8 235 m^2** and the annual number of charges from that installation is presented in Figure 26.

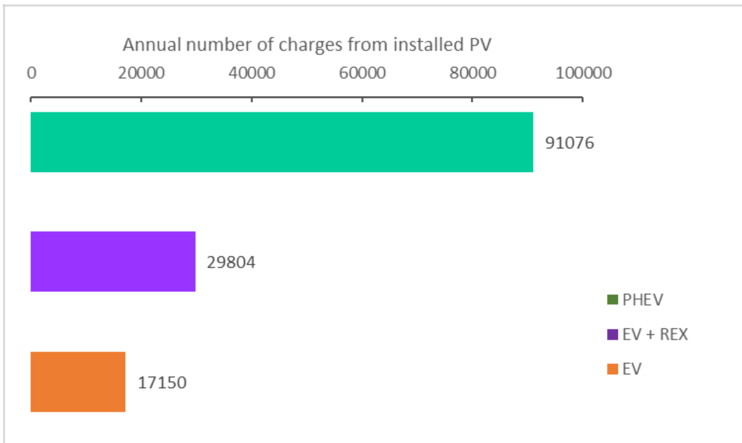

Figure 26. Full vehicle charges supported by upscaled PV installed in Glasgow.

3.3.2.3 Umea System Analysis

The modelling approach described for the Glasgow Car Park system has been extended to analyse performance in the lighthouse cities. Firstly, the ESP-r model has also been simulating using Umeå reference climate data. The seasonal energy yield is shown in Figure 27.

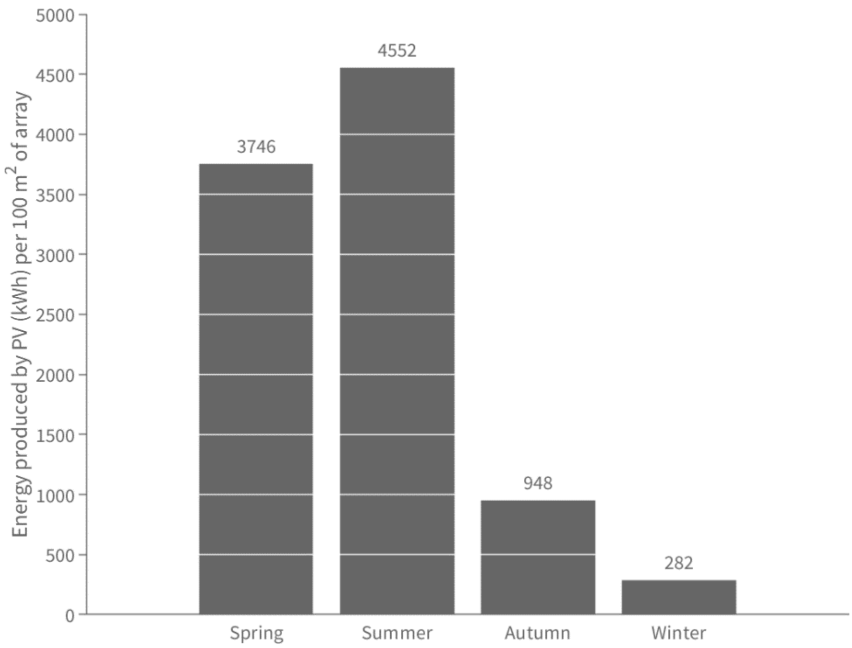

Figure 27: Seasonal energy yield from 100m² of PV modelled with Umeå climate.

The simulated PV output shows significantly more seasonal variation than Glasgow with slightly more generation in spring and summer due to longer days and more direct sunlight, however winter generation is significantly less, probably due to a shorter day length. The annual output is similar: 9 758 kWh/100 m² for Glasgow against 9 528 kWh/100 m² for Umeå. Figure 28 shows the number of annual charges for each electric vehicle type (note the same mix of vehicles as for Glasgow was used to calculate this data). For the seasonal charges for each vehicle type, see Figure 55 in chapter 6 Appendix – Figures.

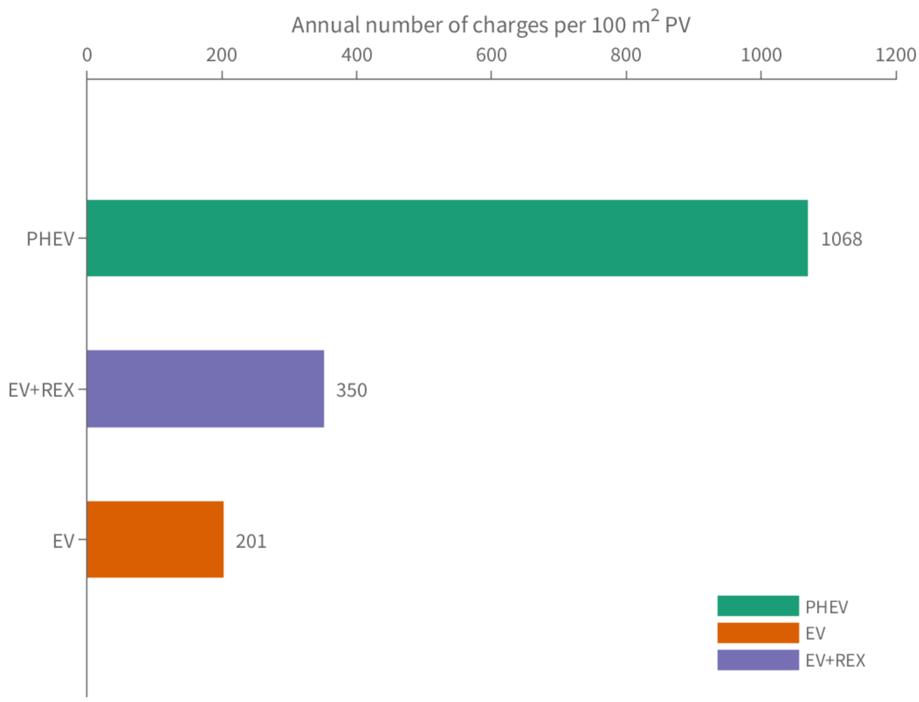

Figure 28: Number of complete charges per vehicle type per 100m² of PV for Umeå.

The possible area of PV that could be installed in **Umeå is 11 048 m²** and the annual number of charges from that installation is presented in Figure 29.

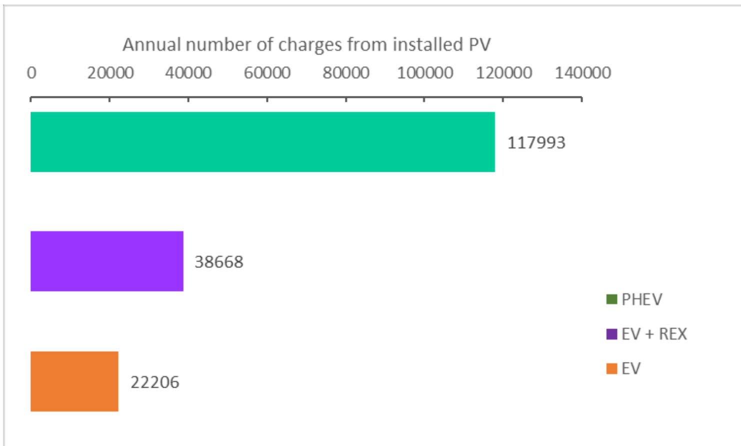

Figure 29. Full vehicle charges supported by upscaled PV installed in Umeå.

3.3.2.4 Rotterdam System Analysis

Modelling the PV and EV system using a reference Rotterdam climate set gives a total energy yield of 11 940 MWh per 100 m^2 – a **yield more than 20% higher than both Glasgow** (9 758 MWh per 100 m^2) **and Umeå** (9 528 MWh per 100 m^2). The seasonal variation in yield is shown in Figure 30. Like the other two cities, this shows that the bulk of the energy from the PV is available in spring and summer, with a marked drop off in yield in autumn and winter.

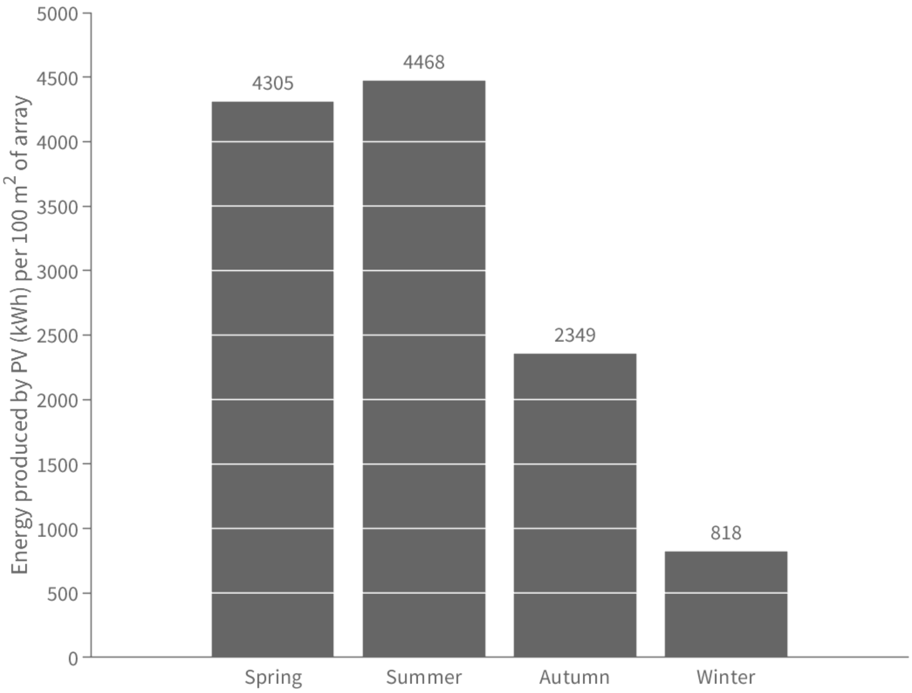

Figure 30: Seasonal energy yield from 100m^2 of PV modelled with Rotterdam climate.

Figure 31 shows the corresponding number of charges achievable for each vehicle type for Rotterdam per 100 m^2 of PV array. Again, a similar vehicle mix to the UK is assumed. For the seasonal charges for each vehicle type supported by the PV array in Rotterdam, see Figure 56 in chapter 6 Appendix – Figures.

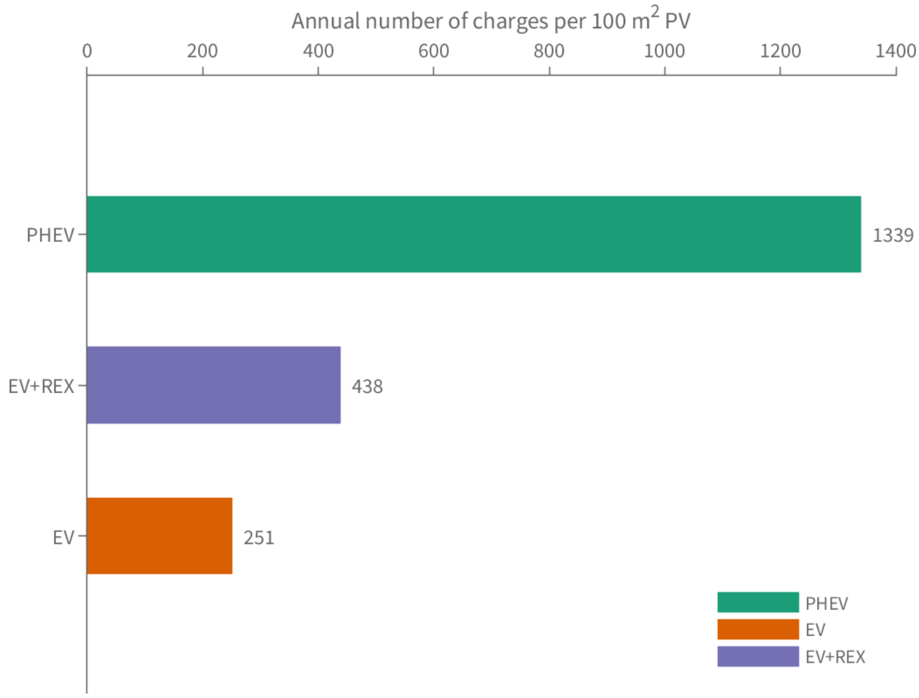

Figure 31: Number of complete charges per vehicle type per 100m^2 of PV for Rotterdam.

The possible area of PV that could be installed in **Rotterdam is 24 465 m^2** and the annual number of charges from that installation is presented in Figure 32.

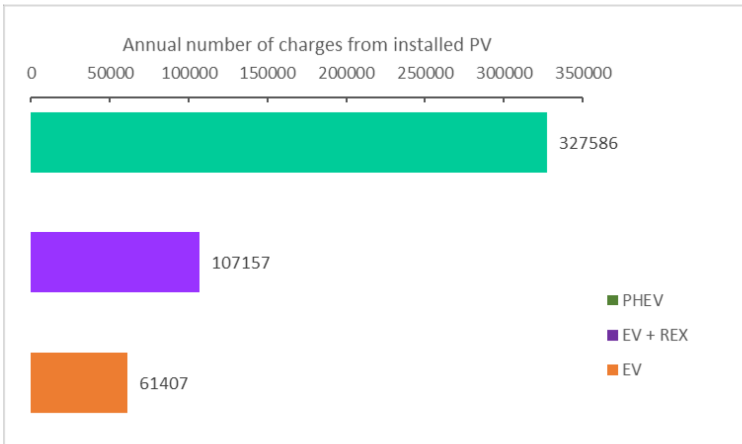

Figure 32. Full vehicle charges supported by upscaled PV installed in Rotterdam.

3.3.2.5 Cost Analysis

The economic benefits of the Glasgow smart hub solution relate to **improvements in running cost. The capital cost is not considered now**, as this is a demonstration, and so capital cost will be significantly higher than would be the case if the technology was established.

Alison and Kelly, (2019) analysed running costs for the Glasgow hub, with to key parameters varied, specifically: the number of vehicles serviced and a battery to maximise the amount of PV generation that was used to support EV charging.

- the battery size was varied between 0 (no supporting battery) and 500 kWh
- the number of vehicles by the hub between 10 and 50.

Additionally, two different battery operating strategies were also analysed:

- the battery was supplied only from the PV, with only emergency input from the grid to maintain a minimum state of charge;
- the battery was charged from the PV but is also topped up to 100% SOC overnight at low tariff periods.

In all cases, the battery preferentially supported EV charging rather than exporting to the network. Power was only exported to the network from the PV array if the battery SOC is at a maximum.

The running cost was estimated through a calculation of the electricity tariff, which was not a flat rate. The electricity tariff comprised: *consumption charges* per unit (kWh) of energy used, and *pass through charges* and each of these in turn has multiple cost components.

The consumption charges consisted of the following.

- *Energy use (E_x)*: the wholesale cost of energy used, which split into two periods, each with a different rate: Day (00:00/07:00), and Night (07:00/00:00). The cost is the same during weekdays and weekends.
- *Infrastructure costs*: These relate to the cost of energy lost as it travels from the power station, through the transmission and distribution wires. The Distribution Use of System (DUoS) is charged at three different rates: Red, Amber, and Green. These bands change depending on time of day and day of the week and are summarised in Table 36. The Transmission Use of System (TUoS) is a fixed charge, given in Table 37.
- *Service Charge (MF)*: These are the costs incurred to the electricity supplier. This is the management fee given in Table 37.
- *Climate change levy (CCL)*: This is a tax on the energy used from the national grid to encourage businesses to reduce their energy consumption or switch to energy from renewable sources. It is paid at a fixed rate per kWh as given in Table 37.

Table 36. Time bands for DUoS charges.

Time periods	Red Time Band	Amber Time Band	Green Time Band
Monday to Friday*	16:30/19:30	08:00/16:30 & 19:30/22:30	00:00/08:00 & 22:30/00:00
Saturday and Sunday		16:00/20:00	00:00/16:00 & 20:00/00:00

Pass through charges are calculated from the following.

- *Standing charge (StC)*: Contributes to the installation and maintenance of the electricity distribution network. This is charged at a daily rate given in Table 37.
- *Agreed supply capacity* (ASc or *maximum import capacity*): This is a charge for the maximum amount of power that can come from the local distribution network at any given time. The site currently has an agreed capacity of 650 kVA and is charged at a monthly rate given in Table 37.
- *Reactive power charge (Rc)*: Reactive power is the difference between the electricity supplied and what is converted into useful energy. This is charged per kVARh and its rate is given in Table 37.
- *Combined half-hourly data charge (HHc)*: The costs associated with collecting and handling half-hourly metering. This is charged at a daily rate given in Table 37.
- *Settlement agency fees (SAF)*: Charge for the distribution companies, suppliers, and metering companies recovering costs from one another. This is charged at a daily rate given in Table 37.

Table 37. Summary of charges.

Consumption-related charges:			
Charge	Unit price (£)	Unit of measure	Symbol
Unit charge (day)	0.07707	per kWh	U_D
Unit charge (night)	0.06613	per kWh	U_N
DUoS charge (green)	0.00093	per kWh	$DUoS_G$
DUoS charge (amber)	0.00935	per kWh	$DUOS_A$
DUoS charge (red)	0.11672	per kWh	$DUOS_R$
Climate change levy	0.00568	per kWh	CCL
Reactive power charge	0.00309	per kVArh	R_C
Fixed charges & pass through charges:			
TUoS charge	30.48098	per month[3]	$TUoS$
Management fee	6.92	per Each bill cycle	MF
Standing charge	0.26340	Daily	StC
Agreed capacity	0.723	per kVA/month	ASC
Combined HH data charges	0.70521	Daily	HHc
Settlement agency fees	0.02302	Daily	SAF

The total annual running cost is therefore:

$$C = U_D E_D + U_N E_N + DUoS_G E_G + DUoS_A E_A + DUoS_R E_R + R_C E_{VA} + CCL\ E_T + (StC + DAT + SAF + HHc)d + (ASC + TUoS)m + MF \quad (1)$$

Where $E_{D,N,G,A,R}$ are the number of real power units (kWh) used in the day, night, green amber and red time periods over the year, respectively. E_{VA} is the total number of reactive power units used over the year and E_T is the total number of units used over the year. Finally, d is the number of days (365) and m is the number of months (12).

A typical variation in operating costs (i.e. electricity cost for supplying power to EVs) is as shown in Figure 33.

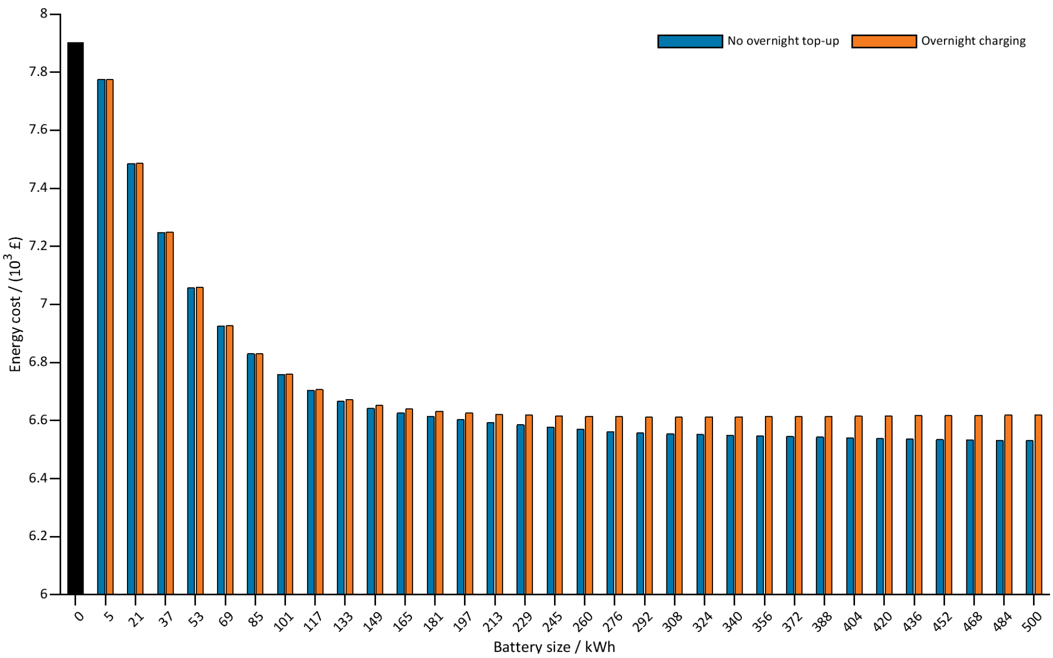

Figure 33. Annual energy cost for 20 EV vs battery size.

This shows that in the range analysed, there is no optimum size of battery or number of EVs, however **there is a distinct 'knee' on the annual energy cost curve, beyond which**

[3] The billing for this quantity is ambiguous regarding the units or calculation method.

increasing the battery size (and capital cost) results in only marginal gains in the annual energy cost. Analysis of the Glasgow data indicated that the battery size beyond which cost benefit was minimal was approximately 8 kWh per vehicle serviced by the hub. The analysis also showed little cost difference between the different operating strategies analysed.

An alternative cost analysis, which does not involve the complicated and place-specific costing equation used in the Glasgow case, looks only at the benefit derived from PV-generated electricity to assist EV charging. This assumes that all of the PV-generated electricity is used for charging by the use of an arbitrarily large battery.

In these cases, the cost of electricity used is:

- Umeå 0.0973 €/kWh
- Glasgow 0.256p/kWh (0.195 €/kWh)
- Rotterdam 0.25 €/kWh

The annual, simple accrued savings (€) due to PV-assisted charging for each of the cities would be as shown in Figure 34.

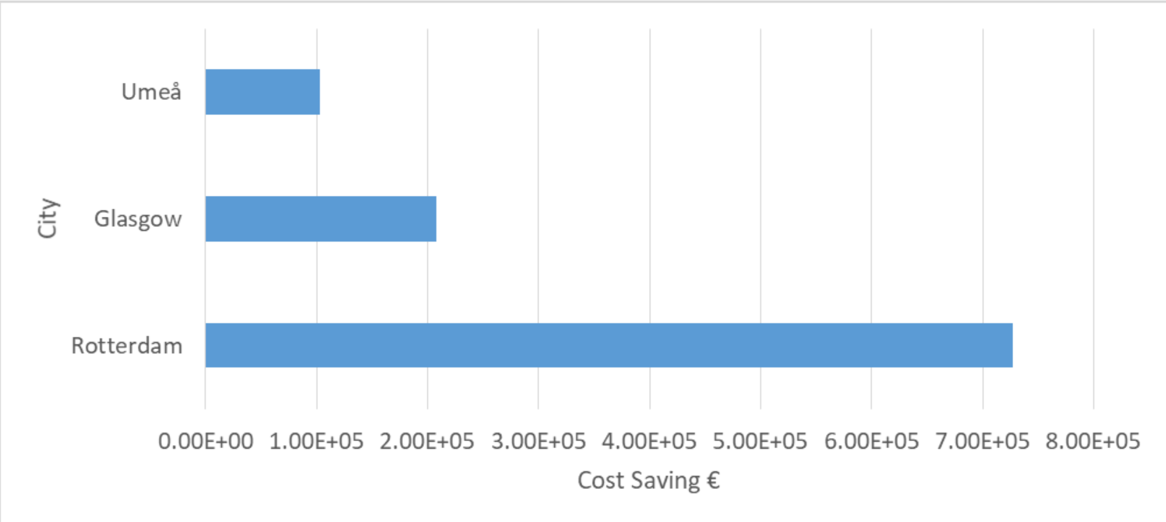

Figure 34. Running cost savings from PV supported EV charging.

3.3.2.6 Carbon Effects

Using the emission factors presented in Table 3 in section 2.2 the **Glasgow** canopy and charging hub **could save over 225 tonnes of carbon per annum**. The figures for **Rotterdam and Umea are 1330 tonnes and 126 tonnes, respectively.**

The modelled data outlined above can act as an input to a decision point in the other lighthouse cities and shows that the same solution applied in different locations can have very different outcomes in terms of its environmental benefit.

3.3.3 Solution G2 and G9

As part of the RUGGEDISED project, the City of Glasgow and its project partners are installing a load shifting system for electric storage heating in the Drygate flats on the City's Duke Street. The load shifting will be complemented by a communal battery installation. **The objective of the load shifting and battery system is to provide greater thermal comfort for end-users, whilst utilising off-peak, lower-carbon electricity.**

The aims of this work are to firstly to quantify the performance of the storage heating and battery system in each of the three cities. The results are presented in terms of energy and carbon savings per m^2 of floor area and kWh of heating demand, so that they can be simply scaled to assess different upscaling levels of the solution in each city.

3.3.3.1 Modelling of the Drygate Flats

The modelling work described here was initially undertaken for Work Package 4 of RUGGEDISED (Task 4.2: *Increase the energy efficiency at the district level*. Specifically, the work contributed to the development of Glasgow smart solutions G2: *Deployment of a suitable battery storage technology for grid balancing*.

The Drygate flats are a group of three, 14-storey high-rise residential blocks located next to Duke St. The flats are used for rented social housing and can typically accommodate 1-2 residents per flat and house over 300 residents in total. Each tower block was originally built in the late 1960s and has since been refurbished with external insulation and improved glazing installed in the early 2000's.

Figure 35. Drygate Flats, Glasgow (image: Dennistoun Online).

All of the flats are electrically heated as in the UK it is not permitted to use gas heating in high-rise residential housing. The heating system employed is storage heating: electrical heating with added thermal mass in the form of high-density thermal block. A typical storage heater is illustrated in Figure 36.

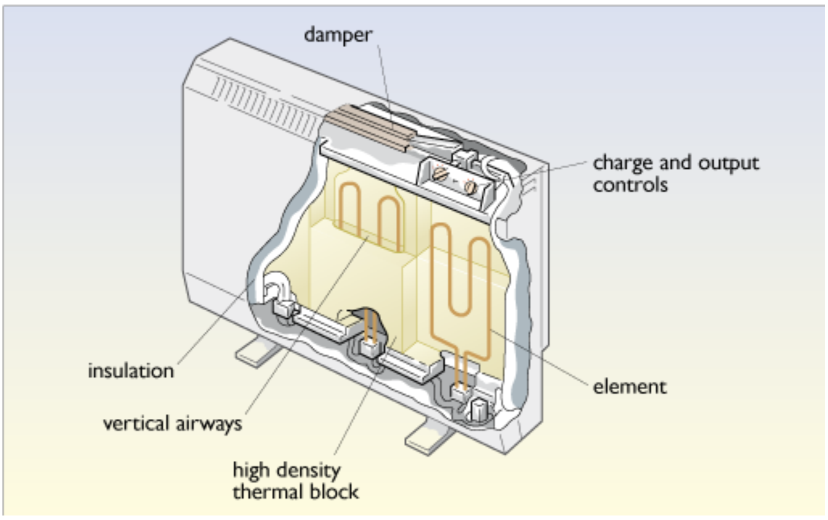

Figure 36. UK Domestic storage heater (image:Open university).

The mode of operation is that the heater will charge overnight, with the block heated using low-cost electricity and reaching temperatures between 400-600 °C. The stored heat is then discharged during the day providing heat for the flat. Historically in the UK, electrical storage heating units provided flexible demand for an electricity network with surplus night time nuclear generation, but provided inadequate levels of thermal comfort for end users due to poor controllability (through manually operated controllers) and an inability to hold charge. Consequently, the reputation of flexible electrical heating is poor.

The load shifting system

The load shifting system to be deployed in the Drygate flats as part of RUGGEDISED, attempts to overcome some of the key shortcomings of storage heating highlighted previously: poor controllability and premature discharge of heat. To achieve this, the system comprises two main elements.

- An automated charge controller, that links the charge delivered to the storage heater to the anticipated thermal demand for the day ahead. Previously, the charge received by the storage heater was selected by the occupant. The controller also shifts the charging period closer to when the heat is required, with a top-up charge delivered during the day if required; this means that the heater will not be depleted of charge by the end of the day.
- A communal battery which charges overnight using low-cost off-peak electricity which supports the operation of the storage heating and heating controller during the day. With the battery in place, it is possible to operate the storage heaters during the day using low-cost electricity supplied by the battery instead of high-cost electricity from the electricity network.

Modelling of the Flats

To assess the performance of the heating control and battery system, a detailed building simulation model of a floor of the Flats has been using the ESP-r building simulation tool (Clarke, 2001). This is shown in Figure 37.

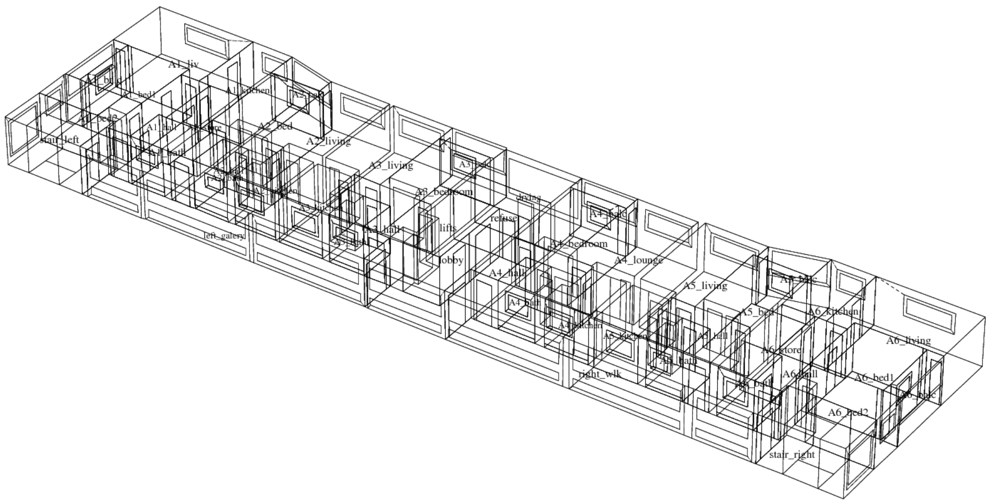

Figure 37. ESP-r model of a floor of the Drygate Flats.

The model shown in Figure 37 is of a single floor of the 14-floor Drygate high-rise block, which comprises six flats, with a total floor area of 260 m^2 and a total heated floor area of 198 m^2. Each flat has 1 or 2 bedrooms, a living room, bathroom, hall and kitchenette. Heating is provided by a 1560 W electric storage heater in the living room and a 1050 W storage heater in each bedroom, consequently the total heating capacity is between 2510 – 3660 W.

The flats from part of a wider RUGGEDISED area model shown in Figure 38, which shows the computer model of the Glasgow smart street.

Figure 38. RADIANCE model of the Duke St. smart street. Simulating the impact of Load Shifting.

The energy performance of the Drygate flats model has been simulated over a one-year time period using half-hourly time intervals and typical Glasgow climate data as a boundary condition. The simulations track all temperatures and energy exchanges occurring in each flat. Typical temperature output is shown in Figure 39, which shows the operative temperatures in a selection of rooms over the first three months of the year.

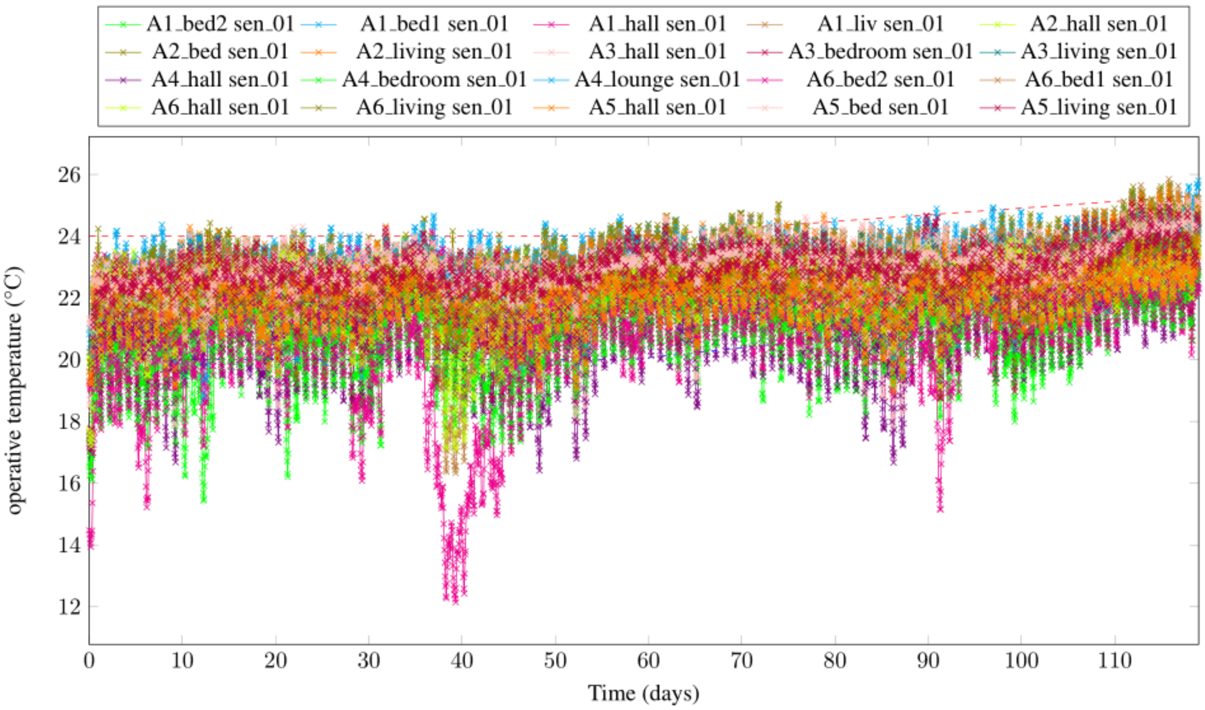

Figure 39. Example of simulated operative temperatures in the flats.

The simulations enable the environmental conditions (e.g. temperatures and air quality) and heating load to be characterised in terms of their time-variation and quantity. To assess the impact of load shifting, two annual simulations are run. These differ by the heating system operating strategy.

In the first simulation, the heating system is operated to follow a UK ‘Economy 8’ time charging schedule, with the storage heating being charging between 23.00-07.00. The stored heat is then released into the flat between 07.00 and 23.00.

In the second simulation, the heating system is charged between 07.00 and 23.00 to maintain room operative temperatures at or above 21 °C, however in this case the electricity to provide the charging of the storage heating is assumed to come from a battery, which itself is charged using low-cost electricity.

3.3.3.2 Load Shifting Systems Performance

The performance of the two strategies was contrasted in terms of the energy used by the heating system and the ability of the system to deliver thermal comfort. Thermal comfort was assessed based on instances of overheating and underheating. For this analysis overheating was defined as temperatures in excess of 25 °C and underheating was defined as temperatures below 18 °C.

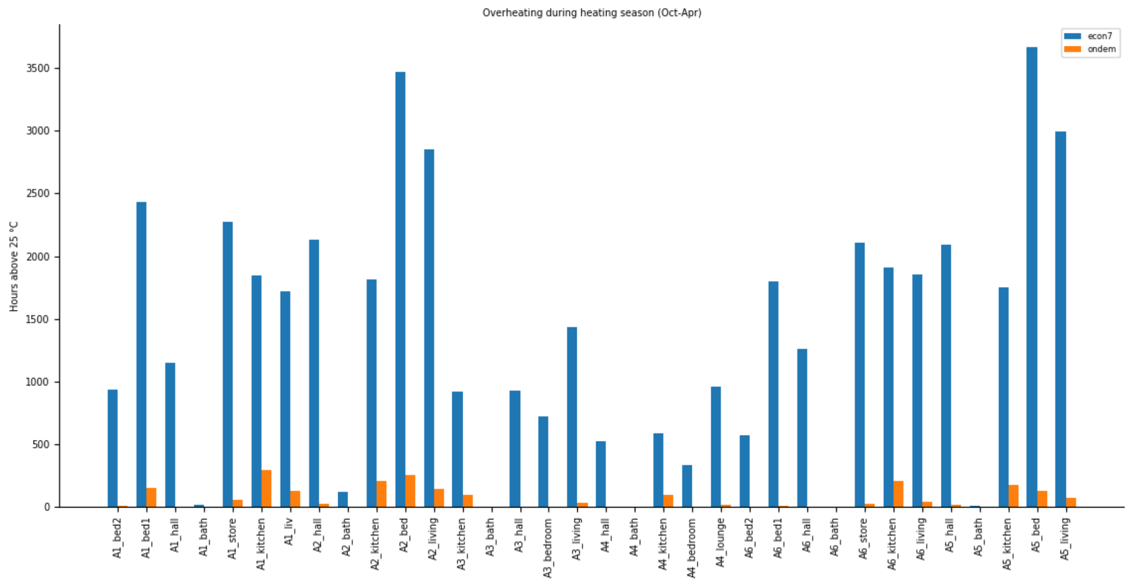

Figure 40. Occurrence of overheating during modelled heating season.

Figure 40 shows that changing the control of the storage heating from overnight charging to on-demand heating results in significant reductions in overheating, which was particularly prevalent in bedrooms. The primary reason for the improvement is that, with on demand heating, heating demand is based on the measured air temperature in the flats, whereas with overnight charging, the charge was delivered based on the temperature of the block inside the storage heater.

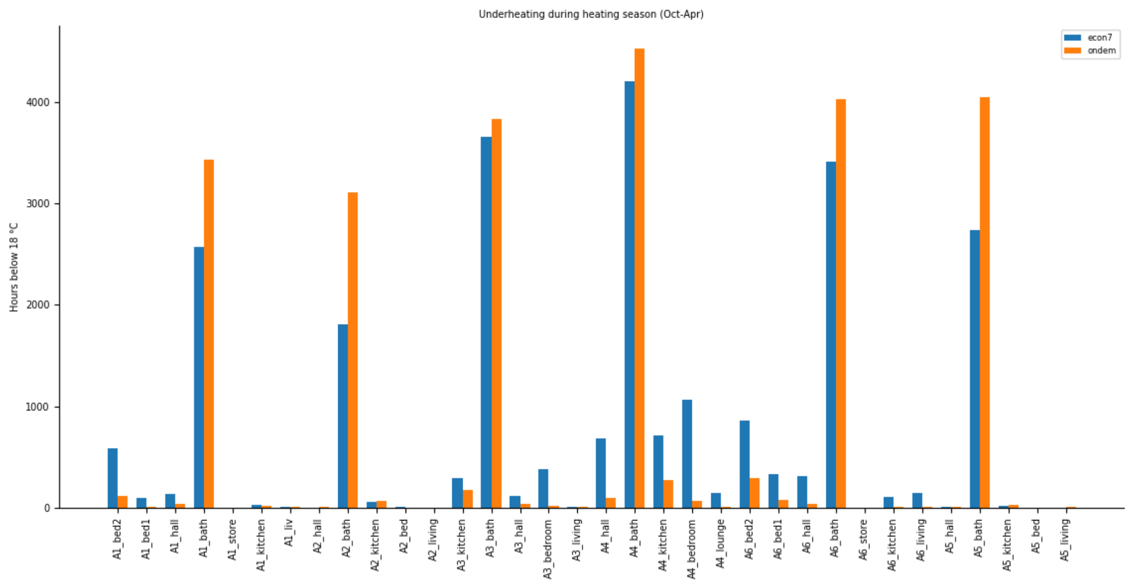

Figure 41. Occurrence of underheating during modelled heating season.

Figure 41 shows that the occurrence of underheating is slightly exacerbated by the switch from overnight charging to on-demand heating, however the vast majority of this underheating occurs in bathrooms, which are infrequently occupied and unheated spaces in the flats.

The heating demand for the flats for both modelled heating operating strategies is shown in Table 38.

Table 38. Heating requirements for flats normalized by floor area.

	Energy use [kWh/m^2]	
Period	**Economy 8**	**On-demand**
Jan-Apr	37.9	34.6
Oct-Dec	28.3	19.9
Total	**66.2**	**54.5**

The switch to on demand heating resulted in a reduction in the heating energy consumption of approximately 18% or 11.7 kWh per m^2 of floor area. As with overheating, the improvement in energy performance is predominantly **due to the control of the storage heating charge being changed from storage block temperature to measured air temperature.**

3.3.3.3 Battery Size Required for Load Shifting

Using the storage sizing approach outlined in (Allison, et al., 2018), **the battery size (kWh) required to fully support load shifting of the electrical heating load** from an Economy 8, off-peak schedule to on-demand heating was calculated as 8.26 Wh per kWh of annual demand, or **9.7 Wh/kWh** (0.53 kWh/m^2) accounting for battery inefficiency; this approach involves scanning the modelled heat demand data to determine the maximum daily heating demand that needs to be covered by the battery.

The battery charge and discharge capacity (kW) was determined by 1) identifying the battery discharge capacity required to support the peak diversified heating load for the flats modelled or 2) the charging capacity required to enable the battery to charge within the required 8-hour off-peak period.

3.3.3.4 Glasgow system analysis

The total annual space heating demand for the Drygate complex is 723 MWh when heating using Economy 8. Consequently, delivered energy savings of approximately 130 MWh per annum would be attainable, if the on-demand heating system was fitted to all flats in the Drygate complex. However, this figure does not account for charge/discharge inefficiencies in the battery. Assuming a round-trip battery charge/discharge efficiency of 84% (Gonzalez-Castellanos, Pozo, & Bischi, 2020) then the likely energy savings would be 109 MWh/year.

With on-demand heating, the battery size required for the 3 Drygate high rise properties would be approximately 5.8 MWh (based on the on-demand heating requirement and, accounting for charging and discharge inefficiencies).

The associated charging demand or the battery storage would be approximately 0.24 MW per high-rise block and 0.72 MW in total; the assumes that the batteries charge for the full 8-hours of the Economy 8 low cost tariff period. However, as the batteries are sized to support the worst case heating load, the charging demand would be less than this for the majority of the time. The total maximum, non-diversified demand from storage heating was 0.73 MW. So, in this case, the battery supported charging makes little difference to the peak demand.

Glasgow has 67 tower blocks in total (GHA, Glasgow Housing Association, 2019) housing around 8000 residents. All have been refurbished since the early 2000's and are of a similar standard to the modelled Drygate flats. Assuming 112 residents per block in Drygate, the average space heating heat consumption per resident is 2.15 MWh/year, with storage heating. So, the projected space heat demand for all similar Glasgow tower blocks would be 17.2 GWh.

If most of these flats use storage heating of a similar type to the Drygate flats, then **the potential energy savings from moving to on-demand heating coupled with battery storage are 2.6 GWh. The required battery storage capacity to achieve these savings would be 138 MWh.**

It should be noted that the smart solution outlines here is applied to a very Glasgow-specific case, where storage heating is operated more effectively to bring about energy savings and comfort improvements. **Electrical heating in Umeå and Rotterdam would typically be done using direct electric heaters or heat pumps.** Consequently, the energy and comfort savings reported for the Glasgow case would not be appropriate as the heating technologies are different. What is relevant, however, when looking at Umeå and Rotterdam is the size of battery that would facilitate the time-shifting of electrical heating demand from peak periods in the morning and evening to periods of lower demand.

3.3.3.5 Umeå system analysis

Umeå has over 70 650 m^2 of housing that is heated using direct electric heating, with an average heating energy consumption of 112.6 kWh/m^2, which is almost double the heating energy consumption of the Glasgow flats. The required battery energy capacity per m^2 of floor area to support this would be 1.1 kWh/m^2; this would entail charging the battery overnight and then running the on-demand heating from the battery. The total battery capacity required for all direct-electrically heated premises in Umeå would be 77 MWh.

Umeå has a further 94 200 m^2 of housing that is heated using heat pumps, with an average electrical heating demand of 89.4 kWh/m^2. A total battery energy capacity of 82 MWh would be required to fully shift this load to off-peak periods. **So, for Umeå a total battery capacity of approximately 159 MWh would be required to support load shifting of the domestic electrical heating load.**

3.3.3.6 Rotterdam system analysis

The electrical heating energy consumption of a typical Rotterdam apartment is 113 kWh/m^2, a very similar figure to the figure for Umeå and significantly more than the refurbished Glasgow high-rise blocks. The required battery energy capacity to fully support load shifting of this demand to off-peak periods is 1.1 kWh/m^2.

Rotterdam has approximately 1000 of the apartment blocks shown in Figure 42, with a total floor area of approximately 2 250 000 m^2. Around 35% of these blocks are electrically heated, which gives an annual electrical energy consumption of 89 GWh. **The total battery capacity required to provide complete load shifting would be 735 MWh.**

Figure 42. Typical Rotterdam apartment blocks.

3.3.3.7 Normalised Battery Capacity

Figure 43 shows the calculated battery capacity (normalised by floor area) required to support load shifting, fully to off-peak (overnight) periods. This shows a significantly smaller battery capacity required for the Glasgow case then either Umeå or Rotterdam. The reason for this is that the Glasgow flats modelled in this report were refurbished to a high standard of insulation and consequently their heating demand is relatively low. Despite having well insulated buildings, Umeå has a significantly longer and colder winter than Glasgow. Further, Rotterdam flats used for scaling were not refurbished and so have a higher energy consumption than the Glasgow flats.

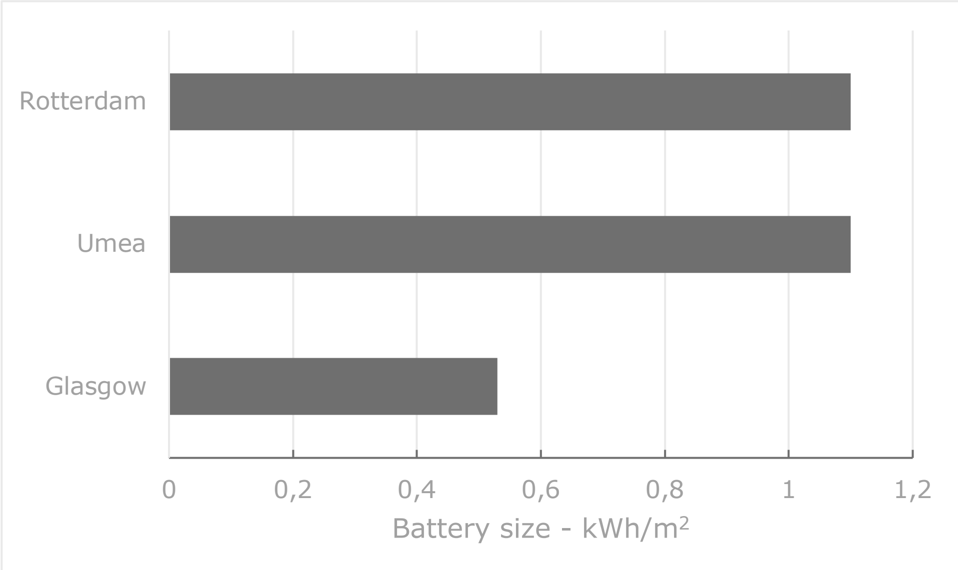

Figure 43. Battery size (kWh) required to fully support load shifting of electrical heating y to off-peak periods (normalised by floor area).

3.3.3.8 Cost Analysis

For the **Glasgow** case, the running cost savings are relatively straightforward to calculate. Assuming that off-peak electricity has a cost of 0.104 €/kWh, then the total savings accrued changing from storage heating to battery + on-demand electrical heating would be approximately **269 600 €.**

The equivalent savings for the other cities cannot be calculated as only Glasgow residents would make the switch from storage heating to battery + on demand heating.

3.3.3.9 Carbon Effects

The carbon savings from this solution for Glasgow are quantifiable in that the modelled energy saving is 109 MWh compared to delivery of heat from storage heaters. This equates to a **saving of approximately 720 tonnes of CO_2 per annum.**

The savings for the other two cities would be more modest and much harder to predict: these already use more efficient heat sources (compared to storage heating) and the addition of a battery store would slightly increase energy taken from the grid due to battery inefficiencies. This would be offset by energy for heating being taken from the grid at off peak times and (probably) lower grid electricity carbon content. However, quantifying this would require time-varying grid carbon data for Sweden and the Netherlands, which was not available at the time of writing.

3.4 Aggregate effects

This section describes the aggregate effects within the three cities if all solutions are implemented and upscaled. This might not be feasible levels of implementation as of today mainly due to financial limitations, but the aim is to get an estimation of how the energy system would be affected if those or similar solutions were to be used on a large scale in the future. **The upscaling effect of the various solutions differ between the cities and solutions. The main factor for this difference is the upscaling level.** This is dependent on the conditions and feasibility of the different solution in the cities e.g. Umeå has a large district heating network which makes the potential for upscaling of heat load shifting for buildings connected to district heating much larger than for Glasgow where the district heating network is much more limited.

It is not possible to sum the upscaling effects of all the solutions since they have different characteristics and impact the energy system in different ways. There are **energy efficiency solutions** that reduce the heat and/or electricity demand, **energy generating solutions** as well as **load shifting solutions** which do not reduce the load but instead shifts it to another point in time. The solutions are also affecting both the electricity and thermal energy system. The aim of this section is to summarise and compare the different solutions and increase the understanding of the upscaling effects through visualisation of the results.

The R1 – smart thermal grid and heat-cold storage is seen as a requirement for the R2, R4 and R8 solutions. In this overall analysis the upscaling potential of these solutions is therefore adjusted to the upscaling potential of the R1 solution to give a more accurate description of the potential.

3.4.1 Rotterdam

The solutions in Rotterdam are focused on **reducing the large dependency on natural gas** in the heating system to keep up with the ambitious climate goals in the Netherlands. The **main focus is to enable local heat-cold exchange** and maximise the use of waste heat-cold through geothermal storage and a low temperature grid. The solutions including the transport system in Rotterdam is to a large extent covered by the G2, G4 and G5 solutions. The aggregate effects of the upscaling in Rotterdam includes these smart solutions:

- R1 – Geothermal heat-cold storage and heat pumps
- R2 – Thermal energy from waste streams
- R4 – Pavement heat cold collector
- R5 – DC grid, PV and storage for mobility (covered by G5)
- R6 – Smart charging parking lots (covered by G5)
- R7 – Optimising the E-bus fleet (covered by G5)
- R8 – Energy management
- U2 – Peak load variation management and peak power control
- U4 – Intelligent building control and end user involvement
- U9 – Demand side management
- G2, G4 & G5 – EV charging hub battery storage and optimization of the integration of near-site RES
- G2 & G9 – Battery-supported load management in high-rise flats

3.4.1.1 Effects on the energy system

The upscaling effects of the energy efficiency solutions in Rotterdam is presented in Figure 44. All numbers are yearly values. The x-axis shows how much electricity that could be reduced and the y-axis how much heat demand could be reduced. The size of the circles represents the upscaling potential and the color represent the cost saving potential of each solution, where a lighter color means a larger cost saving potential. Regarding the Rotterdam solutions, R2, R4 and R8, they are all scaled according to the upscaling potential of the smart thermal grid and heat-cold storage, R1, since the smart thermal grid is a requirement for these solutions. The R1 solution itself is not included in the figure, since it does not reduce the heating or electrical demand for the buildings per se but instead shifts the energy source used for heating and cooling.

The G9 solution, battery supported load management in high-rise flats, is not exactly an energy efficiency measure and as can be seen in Figure 44 it does not reduce neither thermal nor electrical demand. It applies load shifting and a battery system to provide greater thermal comfort for end-users, whilst utilizing off-peak electricity. Around 350 apartment blocks in Rotterdam are suitable for this solution with an annual electrical energy consumption of 89 GWh. To provide complete load shifting to off-peak hours this requires a battery capacity of 735 MWh.

The U2 solution, peak load variation management and peak power control is also a load shifting solution but is also assumed to reduce the heating demand with 17 GWh due to monitoring and smart control installed, as can be seen in the figure. This solution also makes it possible to shift 95.5 MW of heat load for four hours to avoid peak power production of district heating, which is not seen in the figure.

The U4 solutions intelligent building control is upscaled to 20% of the office floor area in Rotterdam. This makes it possible to reduce the electricity demand with 10.6 GWh of electricity per year. The cooling demand is also reduced and since that is mainly supplied by electricity it is therefore added to the electrical demand reduction in the graph, which result in a total yearly electricity reduction of 14.3 GWh. The heat demand is modelled to increase with almost 1.9 GWh, which is shown by the negative thermal value.

Both R8 and U9 are demand side management solutions, where the R8 solution is applied to buildings connected to the smart thermal grid and the U9 can be applied as a complement to the U2 and U4 solutions, mainly in large office buildings. It can be seen that the upscaling effects on the electricity system is more pronounced by the U9 solution while the R8 solution reduces the heating demand to a larger extent. The upscaling potential with respect to building area for the R8 solution is assumed to be 2/3 of the U9 upscaling potential.

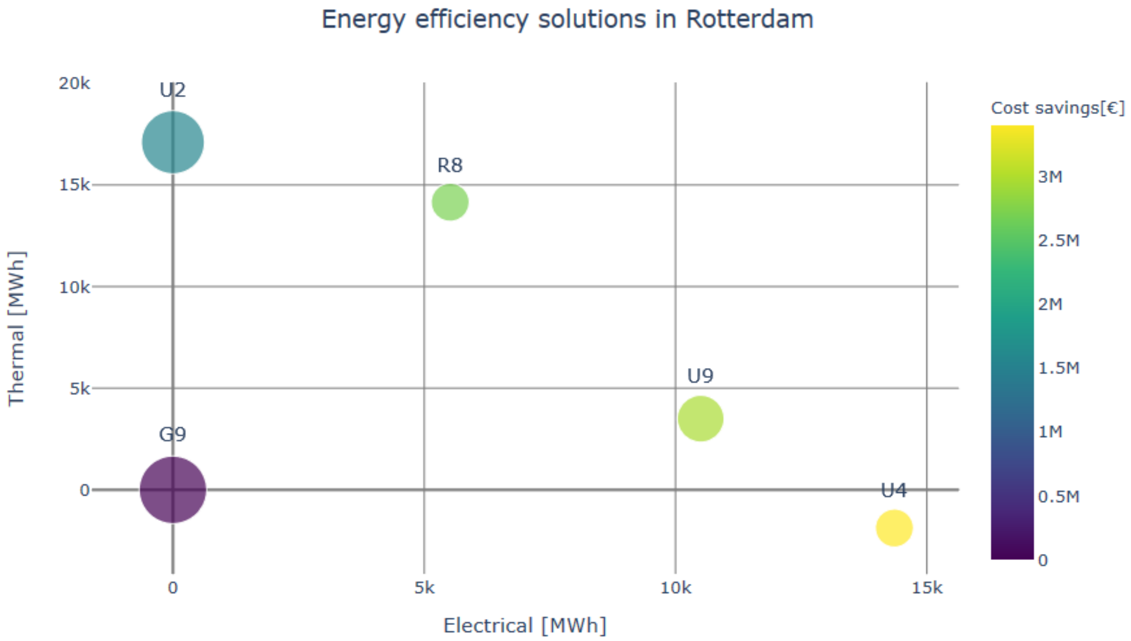

Figure 44. Electrical and thermal effects of upscaling the energy efficiency solutions in Rotterdam. The size of the circles represents the upscaling area and the color of the circle is the cost saving potential.

The upscaling potential of the energy generating solutions are presented in Figure 45. It can be seen that the solutions are generating either heat or electricity.

As stated earlier, the upscaling potential of the R4 and R2 solution are here adjusted to the upscaling potential of the R1 solution, since that is seen as a requirement for the others to be useful. The upscaling of the R4 solution has the largest effects on the energy system with a yield of 43 GWh of heat by implementing the pavement heat collectors to 220 km pavement with a width of 1.47 m. This is enough to supply the base heat demand of the 724 000 m^2 office and residential buildings connected to the upscaled smart thermal grid.

The size of the circles represents the upscaling potential, which is why the dot for R2 solution, thermal energy from waste streams is not visible. The upscaling potential of this solution is expressed in number of pumping stations in Rotterdam, while for the other solutions it is expressed in m^2. By making use of the energy in the wastewater at 4 of the pumping stations in Rotterdam it is possible to yield almost 3.8 GWh of thermal energy per year.

The analysis of G2, G4 & G5 (represented by G5 in the figure), shows that an upscaling of solar PV's to 24 465 m2 of city centre car parks generate around 2.9 GWh of electricity which is enough to supply approximately **330 000 charges of PHEVs**, 110 000 charges of EVs + REX and 60 000 charges of EVs during one year.

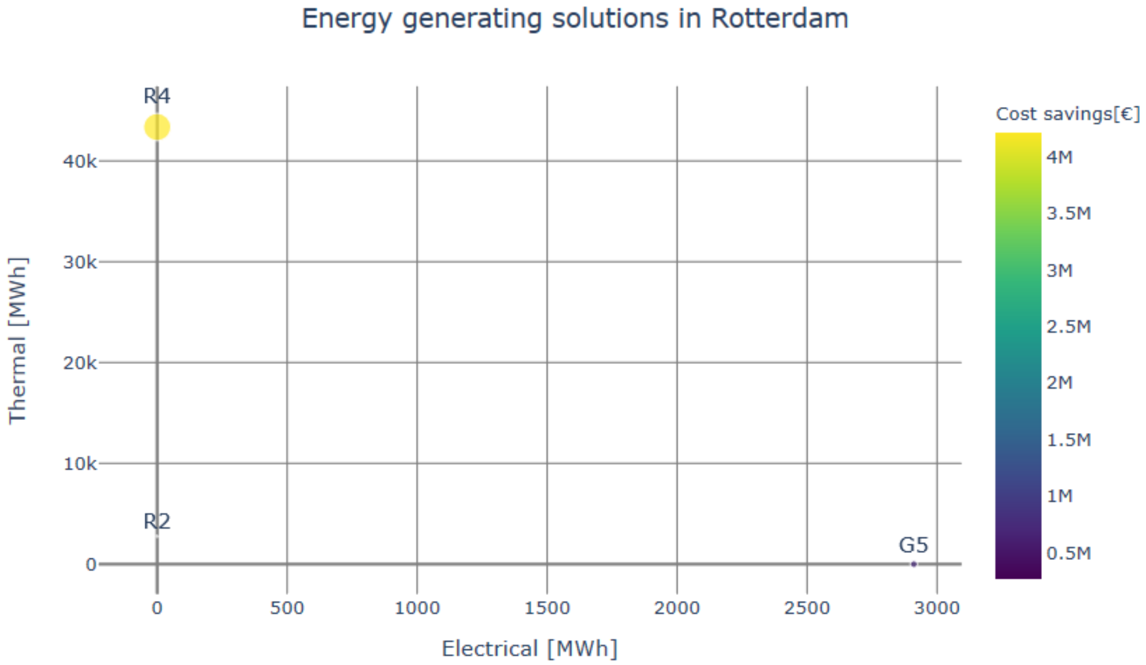

Figure 45. Electrical and thermal effects of upscaling the energy generating solutions in Rotterdam. The size of the circles represents the upscaling area and the color of the circle is the cost reduction potential. The upscaling potential of R2 and G5 is very small compared to the other solutions, which is why these dots are very small

3.4.1.2 Summary and recommendations

The yearly upscaling effects, in terms of energy and CO_2 emissions, of the different solutions is visualised in Figure 46. The energy effects includes both thermal and electrical energy in this figure. The size of the circles represent the size of the upscaling and the color the cost reduction potential.

As can be seen both R4 and R8 has large energy and CO_2 reduction potential. The cost saving potential is also big for the R4, pavement heat-cold collector but it should also be noted that to achieve this, pipes have to be installed in 220 km pavement in the city of Rotterdam, to harvest the available heat. This is associated with a large investment cost. The R1 solution is included in this graph, showing the CO_2 emission reduction and cost saving potential due to shifting from natural gas to heat pumps, utilising the energy from R4 and R2.

Summarising all of the smart solution **energy savings,** gives a figure of some **112 GWh or around 2% of the annual energy consumption** in the city of Rotterdam of 5.4 TWh which includes the housing and service-sector (including also industry and transport the overall total would be 42.6 TWh). This represents both the electrical (including cooling) and heat savings. The yearly CO_2 reduction by upscaling these solutions is around 36 000 tonnes. The yearly energy cost savings that could be achieved are 17.17 M€.

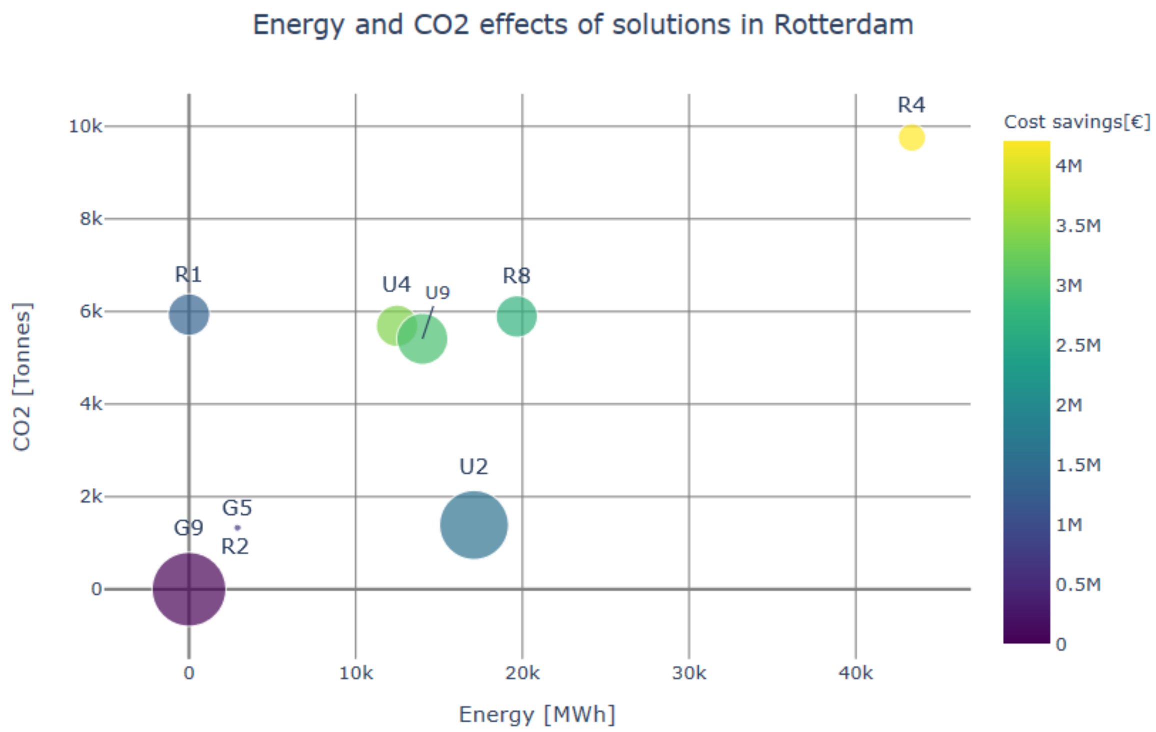

Figure 46. Energy and CO2 effects of upscaling the solutions in Rotterdam. The size of the circles represents the upscaling area and the color of the circle is the cost reduction potential. The upscaling potential of R2 and G5 is very small compared to the other solutions, which is why these dots are very small.

It is the **solutions demonstrated in Rotterdam that also have the largest scaling potential in the city.** This is probably because these are best suited for the Rotterdam conditions, it is also applicable solutions to reduce the gas dependency in the city. Due to the aim of reducing carbon emissions smart thermal grids could be of interest, mainly for new establishments in the city, where in any case an investment in a new energy system has to be made. By utilising waste streams, it is possible to supply many buildings with heat **without exploiting primary resources for heat generation**. However, the Rotterdam solutions have yearly cost savings due to lower running costs than alternative energy sources, which is a incentive for this kind of solutions.

It should also be mentioned that the U4 and U9 solutions has a large yearly CO_2 reduction and it must be considered as easier solutions to implement by using sensors and control equipment to regulate lighting and indoor climate through the ventilation, heating and cooling systems.

3.4.2 Umeå

In Umeå the solutions **are focused on reduction of energy demand, load shifting in the heating system and reduction of the overall emissions** caused by the energy generation and transportation in the city. The aggregate effects of upscaling in Umeå, includes these smart solutions:

- U2 – Peak load variation management and peak power control
- U4 – Intelligent building control
- U6 – E-charging infrastructure (covered by G2, G4 & G5)
- U9 – Demand side management
- R1 – Geothermal heat cold storage and heat pumps
- R2 – Thermal energy from waste streams
- R4 – Pavement heat cold collector
- R8 – Energy management
- G2, G4 & G5 – EV charging hub battery storage and optimization of the integration of near-site RES (also covers U6)

- G2 & G9 – Battery-supported load management in high-rise flats

3.4.2.1 Effects on the energy system

To make the comparison easier and increase the understanding of the upscaling effects, this section includes a visualisation of the results. Figure 47 shows the electrical and thermal effects of upscaling the energy efficiency solutions in Umeå. The size of the circles represents the upscaling area and the colour of the circle is the cost reduction potential. Regarding the Rotterdam solutions, R2, R4 and R8, they are all scaled according to the upscaling potential of the smart thermal grid and heat-cold storage, R1, since the smart thermal grid is a requirement for these solutions. The R1 solution itself is not included in the figure, since it does not reduce the heating or electrical demand for the buildings per se but instead shifts the energy source used for heating and cooling.

The upscaling of the U2 solution, peak load variation management and peak power control makes it possible to reduce the energy demand in the buildings with 15 GWh per year, which corresponds to around 1.7% of the total heat sold by Umeå Energi in 2018 (Energimarknadsinspektionen).

The G9 solution, shifting of electrical heat load is upscaled to approximately 165 000 m^2 floor area, which is equivalent to around 1300 single family houses or 200 multi-family residential buildings in Umeå. The effect of this solution is not captured in Figure 47 since it does not affect the absolute value of electricity demand. However, the upscaling of this solution shows that a 159 MWh battery is required to shift heat load from peak hours for these direct electric heated or heat pump heated buildings. This would reduce the demand of peak power production and most probably the CO_2 emissions, since the CO_2 emissions often are higher during peak power demand.

With an upscaling of U4, intelligent building control, to approximately 956 000 m^2 building area, mainly including offices and university buildings it is possible to reduce the electricity demand in Umeå with approximately 14 GWh per year, due to steering of ventilation and lighting etc. The cooling demand also decreases and if it is supplied by cooling machines with a COP of 2.7, the total electricity reduction is around 17.5 GWh as can be seen in Figure 47. Electrification of different sectors is widely discussed in Sweden and these energy efficiency measures for reducing electricity demand can be seen as one way to mitigate the impact on the electricity system. In the perspective of this analysis, both G9 and U4 could help reduce the impact of increased electricity demand due to charging of EV's.

Both R8 and U9 are demand side management solutions, where R8 is applied in buildings connected to the smart thermal grid and U9 can be seen as a complement to U2 and U4 solutions. The upscaling potential of R8 is considered to be 44% of the upscaling potential of the U9 solution. With these upscaling levels U9 has larger impact on the electricity demand while R8 affects the thermal demand a bit more. Both of these solutions include a behavioural aspect of people, which might be more difficult to change than technical systems. This solution is focusing on increasing the resource efficiency, by using buildings and services more efficiently, and for U9 this might require people to relocate during time periods to get the most out of the solution.

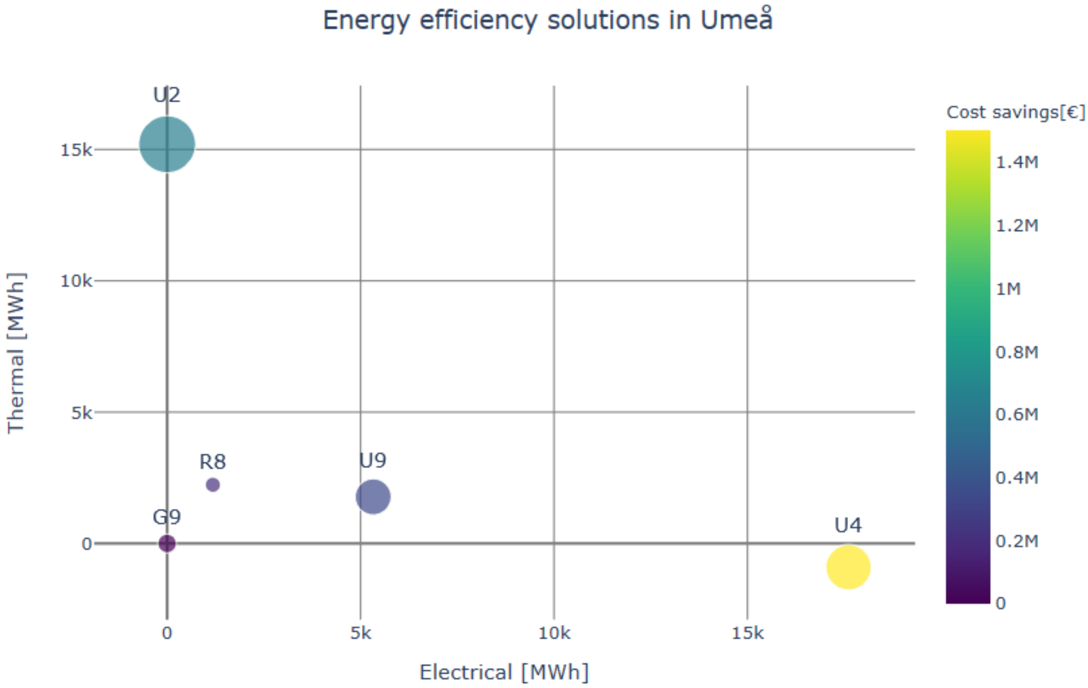

Figure 47. Electrical and thermal effects of upscaling the energy efficiency solutions in Umeå. The size of the circles represents the upscaling area and the color of the circle is the cost reduction potential.

The upscaling potential of the energy generating solutions are are presented in Figure 48. It can be seen that the solutions are generating either heat or electricity.

The R4 solution has the largest modelled effects of the energy generating solutions when upscaled in line with the R1 potential in Umeå. As can be seen in Figure 48, it has the potential to yield 14 GWh of thermal energy through the pavement heat collectors, when upscaled to 95 km of pavement with a width of 1.47 m. The yearly cost reduction is approximately 580 k€ which should be compared with the investment cost of installing pipes in such a large area of pavement. Since this solution is demonstrated in combination with smart thermal grid it would mainly be profitable at new establishments since it is too expensive to exchange an existing heating system. The implementation of the R4 solution might also be easier if planned ahead for a new establishment. Other positive aspects of the R4 solution, is the increased safety by heating the pavement, since it reduces the risk of slippery pavements. It also increases the lifetime of the pavement. In Umeå where there are quite cold and a lot of snow the safety aspect is highly relevant, but it might be possible to solve this by putting the district heating pipes less deep.

When upscaling the R2 solution in accordance with the R1 solution, it is assumed to yield 0.6 GWh of thermal energy from wastewater. The locations of the wastewater pumping stations in Umeå is not known, but since the upscaling potential of the R1 solution is approximately 112 000 m2 it is assumed that only one of the pumping stations is within adequate distance.

Upscaling of the EV charging hub solution to approximately 25 000 m^2 city centre car parks generate 1.05 GWh electricity which is enough to supply **117 992 charges of PHEV** or 38 668 charges of EV's + REX or 22 206 charges of EV during one year. This can be compared to the electric car fleet in Umeå in 2018 with 161 EVs, 1042 EV+REX and 358 PHEV (Lindfors, 2019). The PV generation is not evenly distributed throughout the year, which makes it more difficult to match it with charging of electrical vehicles. The PV generation is largest during summer while the demand for charging could be assumed to be highest in autumn and winter, when people usually uses their car more frequent.

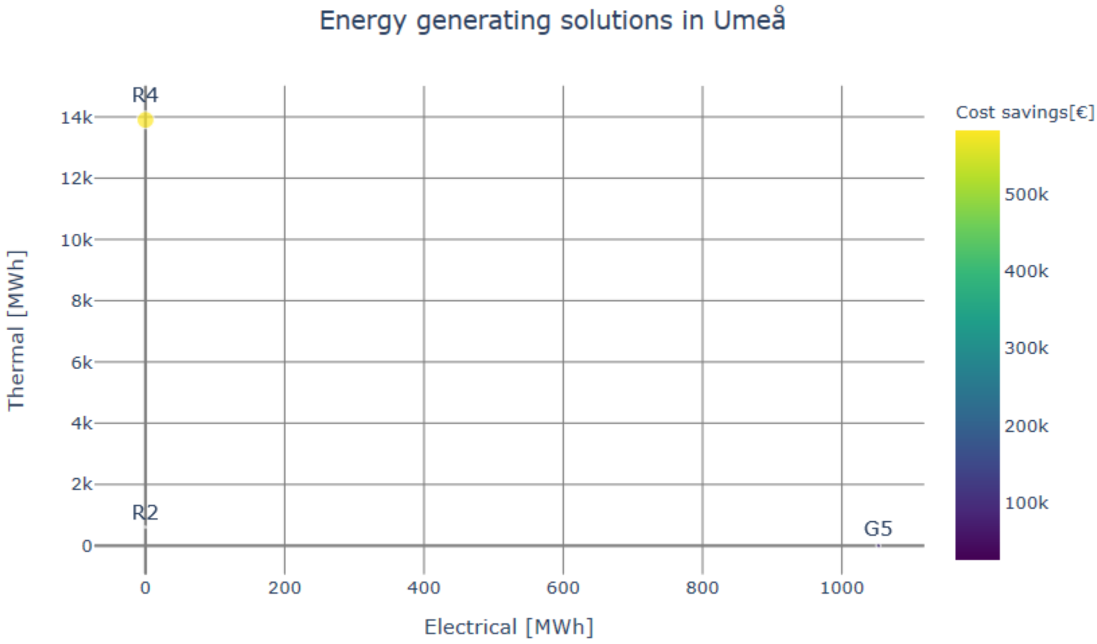

Figure 48. Electrical and thermal effects of upscaling the energy generating solutions in Umeå. The size of the circles represents the upscaling area and the color of the circle the cost savings potential. The upscaling potential of R2 and G5 is very small compared to the R4 solution, which is why the dots is not visible.

3.4.2.2 Summary and recommendations

Figure 49 illustrates the total effect on CO_2 emissions and energy, which includes both thermal and electrical energy. The size of the circles represents the upscaling area and the colour of the circle, the cost saving potential. The lighter the colour the larger the potential.

The R1 solution is included in this graph, showing the CO_2 emission reduction and cost saving potential due to shifting from district heating to heat pumps, utilising the energy from R4 and R2.

The largest potential for both energy and CO_2 reduction has the U4 solution, intelligent building control, which also has a large upscaling potential. Compared to the U2 solution, this is mainly affecting the electrical heating demand, seen in Figure 47 earlier.

As described earlier, the U2 solution, peak load variation management and peak power control both makes it possible to reduce heat demand and shift load. By upscaling the U2 solution to approximately 1630 buildings in Umeå it is possible to reduce heat demand with around 17 GWh as well as shift 50 MW of the heat load for four hours. This makes it possible to reduce the oil fuelled production to 3% of the level in 2019 and with the eight-hour load shift of 25 MW it is reduced to 27% of the level in 2019. This reduces the CO_2 emissions with more than 800 Tonnes per year.

It can be noticed in this graph that it is the solutions demonstrated in Umeå that are also assumed to have the largest scaling potential in the city. This is probably because these are most suited for the Umeå conditions. The G5 solution, representing the U6 solution, has a large percental upscaling potential 75%, but since it is only applied to parking garages, the absolute scaling potential of PV installations is 11 048 m^2.

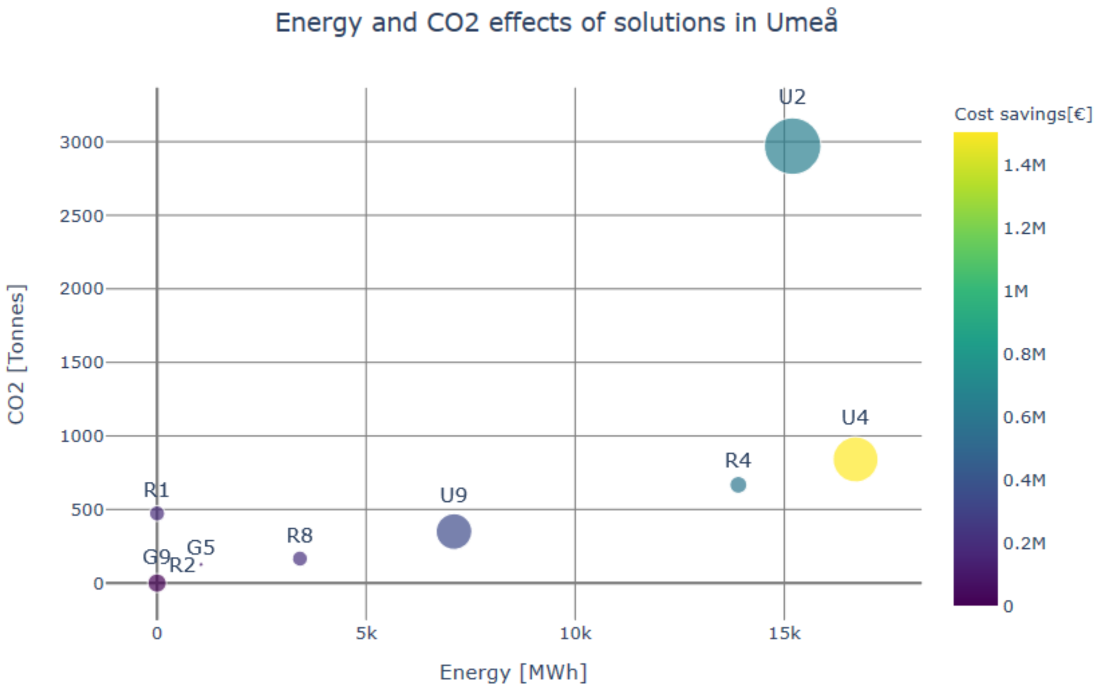

Figure 49. Energy and CO2 effects of upscaling the solutions in Umeå. The size of the circles represents the upscaling area and the colour of the circle is the cost reduction potential. The upscaling potential of R2 and G5 is very small compared to the other solutions, which is why these dots are very small.

Summing all of the smart solution **energy savings** gives a figure of **58 GWh or around 1.2% of the annual energy consumption** in the city of Umeå of 4.92 TWh (Statistiska centralbyrån, 2019), which include all sectors (agriculture, industry, transport, buildings, public sector and others). The yearly CO_2 reduction with an upscaling of these solutions and by excluding the overlapping ones, is around 5 622 tonnes. The yearly energy cost savings that could be achieved are 3.6 M€.

The energy production in Umeå has relatively low emissions, but it is still of value to reduce the energy demand and increase the share of renewables in the system, since the **local system is connected to both national and international systems**. If less power is used in cities in Sweden, the energy produced here with low emission rates could be exported and replace other higher emitting generation units in Europe.

When the level of renewable and intermittent sources increases in the electricity system it will probably be **more important with load shifting** and the possibility to manage the demand side to achieve a secure and robust electricity system. As of today, it might not be profitable to invest in the different solutions for increasing the flexibility in the system, but with an increased demand for flexibility, the value of this service might also increase, making the RUGGEDISED solutions increasingly profitable.

3.4.3 Glasgow

The **aims of the Glasgow solutions** analysed are numerous including **improving the sustainability of city transport, reducing air pollution** through use of electric vehicles (EVs), **reducing the environmental and network impacts of electric heating, improving thermal conditions for vulnerable tenants and reducing energy costs**. The upscaling of the following solutions is reported on here.

- U2 – Peak load variation management and peak power control
- U4 – Intelligent building control (also covers G10)
- U9 – Demand side management
- R1 – Geothermal heat cold storage and heat pumps
- R2 – Thermal energy from waste streams
- R4 – Pavement heat cold collector
- R8 – Energy management

- G2, G4 & G5 – EV charging hub battery storage and optimization of the integration of near-site RES (also covers U6)
- G2 & G9 – Battery-supported load management in high-rise flats

3.4.3.1 Effects on the energy system

The upscaling effects of the energy efficiency solutions in Glasgow is presented in Figure 50. All numbers are yearly values. The x-axis shows how much electricity that could be reduced and the y-axis how much heat demand could be reduced. The size of the circles represents the upscaling potential and the color represent the cost saving potential of each solution, where a lighter color means a larger cost saving potential. Regarding the Rotterdam solutions, R2, R4 and R8, they are all scaled according to the upscaling potential of the smart thermal grid and heat-cold storage, R1, since the smart thermal grid is a requirement for these solutions. The R1 solution itself is not included in the figure, since it does not reduce the heating or electrical demand for the buildings per se but instead shifts the energy source used for heating and cooling.

The largest predicted effect of the energy efficiency solutions is that of Rotterdam's energy management solution R4. If upscaled in line with the R1 solution, modelling indicates that thermal energy savings of 4.9 GWh are possible as well as 1.9 GWh of electrical energy savings.

Implementing solutions G2 and G9 (represented with G9 in Figure 50) and wholly-load-shifting the electrical demand of high-rise flats in Glasgow to off-peak low demand periods would require some 138 MWh of battery capacity. Combined with on demand heating, this could result in a reduction in annual electrical demand for heating of some 2.6 GWh.

Scaling of Umeå solution U4, intelligent building control, which improves control of heating, lighting and cooling in office buildings has the potential to reduce electrical demand across the city by approximately 1.9 GWh, while the heating demand is increased with 0.37 GWh.

Umeå's U9 solution, demand side management is assumed to be applicable to approximately 10% of the office buildings in the city and could result in energy savings of 7% or 1.2 GWh/year

Scaling of Umeå solution U2, which uses flexibility in building demand to reduce peak demand in district heating systems coupled with monitoring and smart control of demand. When applied to Glasgow, these elements have the potential to reduce demand by 2.9 GWh in city centre buildings and shift approximately 8.5 MWh of heat demand.

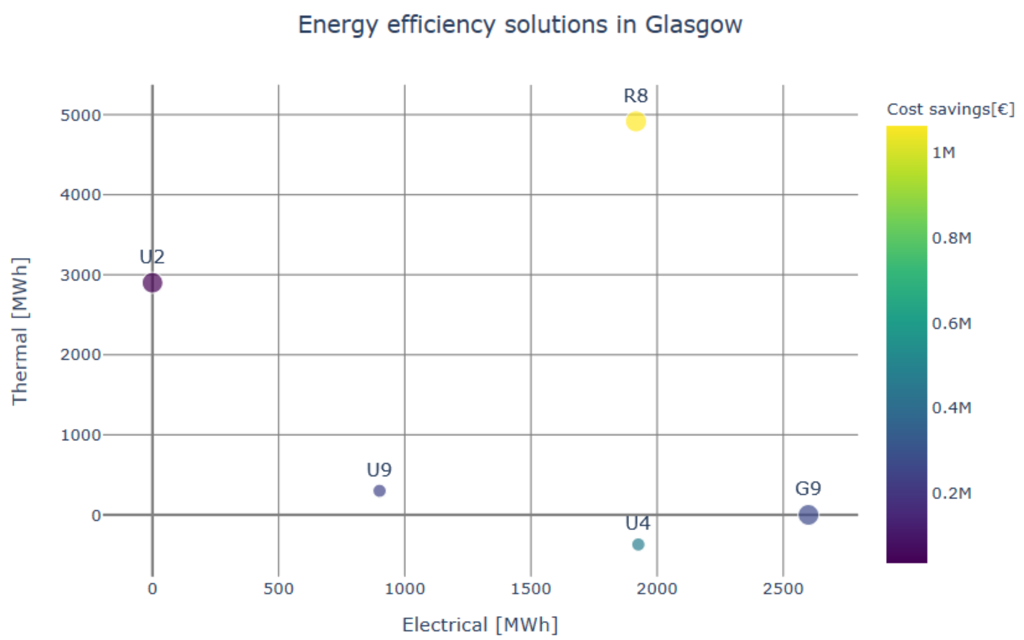

Figure 50. Electrical and thermal effects of upscaling the energy efficiency solutions in Glasgow. The size of the circles represents the upscaling area and the color of the circle is the cost reduction potential.

The upscaling potential of the energy generating solutions are are presented in Figure 51Figure 45. It can be seen that the solutions are generating either heat or electricity.

As the technology can be applied to a very large area of paving, upscaling of Rotterdam solution R4, pavement heat collectors upscaled to the R1 solution could potentially yield almost 19 GWh of heat. By far the largest thermal energy source of the solutions modelled. This requires an upscaling to almost 120 km of paving with a width of 1.47 m. It has the largest yearly cost reduction potential with around 1 M€, but this does not consider the investment cost of installing the pipes.

Upscaling of Rotterdam solution R2, thermal energy from waste sewage streams result in a usable low-grade thermal output of some 2.5 GWh/year that could be utilised by the heat pumps in buildings connected to the smart thermal grid.

The analysis of G2, G4 & G5 (represented by G5 in Figure 51), shows that an upscaling of solar PV's to 8 235 m^2 of city centre car parks generate around 0.8 GWh of electricity which is enough to supply approximately **91 000 charges of PHEVs,** 30 000 charges of EVs + REX and 17 000 charges of EVs during one year.

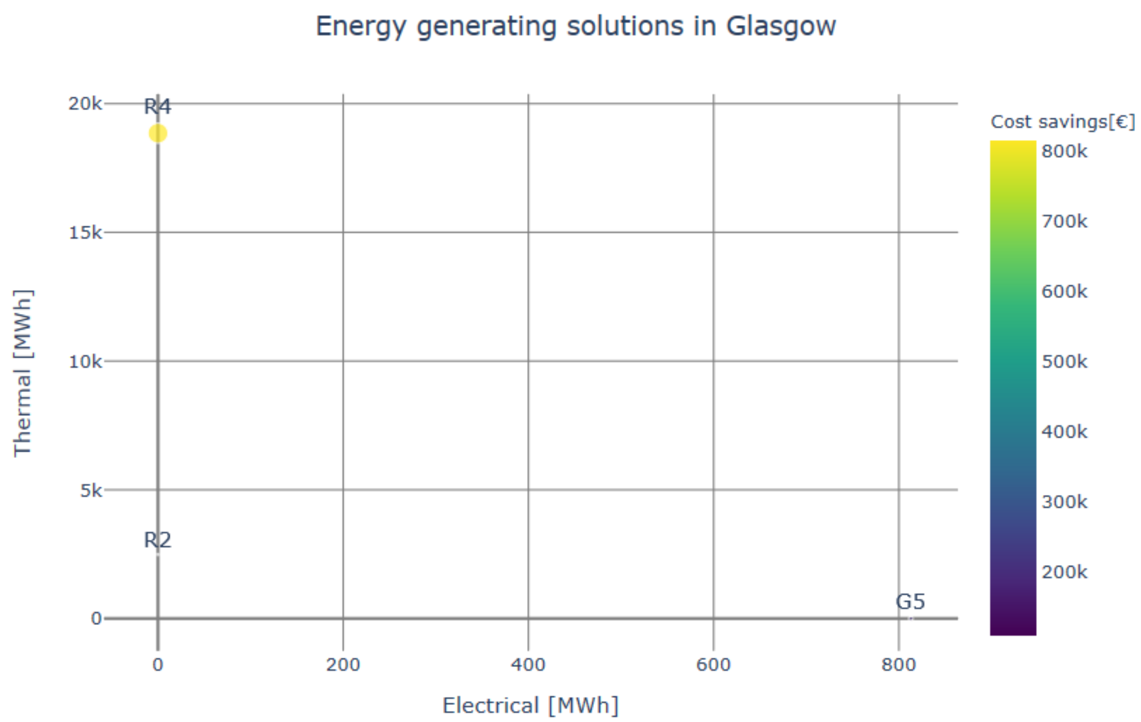

Figure 51. Electrical and thermal effects of upscaling the energy generating solutions in Glasgow. The size of the circles represents the upscaling area and the color of the circle is the cost reduction potential. The upscaling potential of R2 and G5 is very small compared to the other solutions, which is why these dots are very small

3.4.3.2 Summary and recommendations

The yearly upscaling effects, in terms of energy and CO_2 emissions, of the different solutions is visualised in Figure 52. The energy effects includes both thermal and electrical energy in this figure. The size of the circles represent the size of the upscaling and the color the cost reduction potential.

As can be seen both R4 and R8 have large energy and CO_2 reduction potential. The cost saving potential is also big for these two solutions, with the largest potential for R8, energy management. This is most probably also a much cheaper solution to implement since it requires sensors and computing capacity instead of installing pipes in pavement as for the R4. The R1 solution is included in this graph, showing the CO_2 emission reduction and cost saving potential due to shifting from natural gas to heat pumps, utilising the energy from R4 and R2. As can be seen this impose an increase in cost, since the electricity is more expensive than the natural gas. This is the case even when the COP of the heat pumps is included.

Compared to the other cities, the upscaling area of the different solutions is more homogenous in Glasgow. Disregarding R2 and G5 solution, the smallest upscaling area, which is U9 and U4, is 40% of the largest one, which is R8 closely followed by G9.

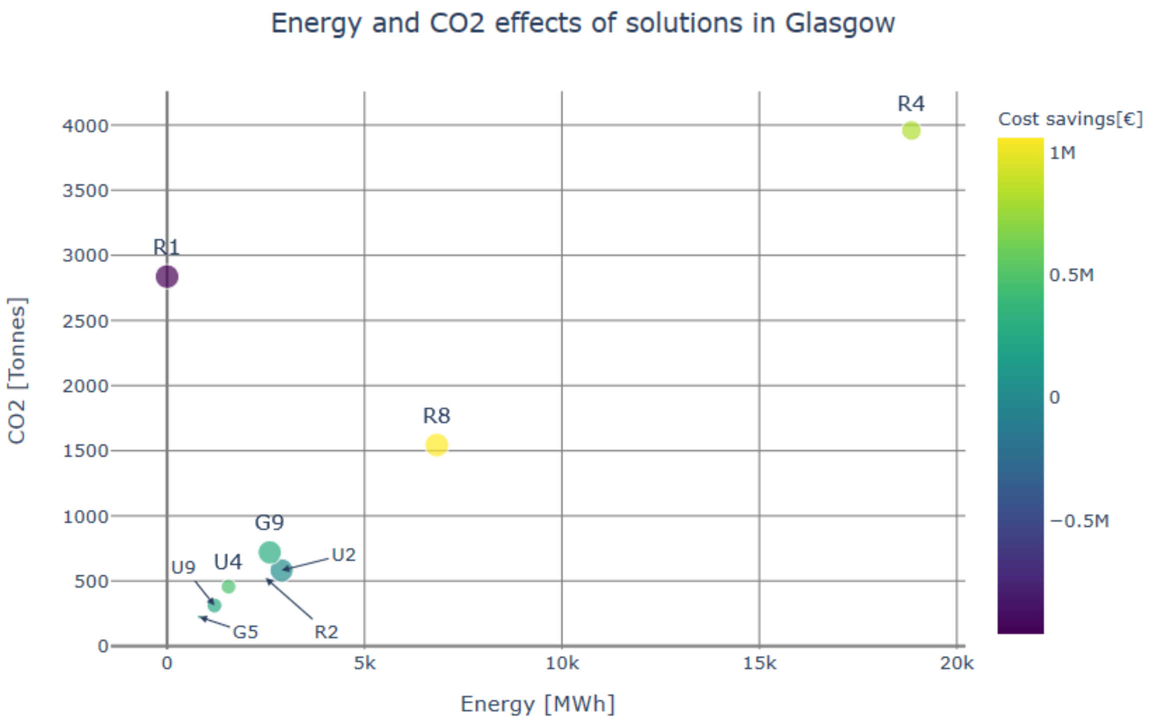

Figure 52. Energy and CO2 effects of upscaling the solutions in Glasgow. The size of the circles represents the upscaling area and the color of the circle is the cost reduction potential. The upscaling potential of R2 and G5 is very small compared to the other solutions, which is why these dots are very small.

The solutions highlighted, if implemented at the large scale have the potential to contribute to improving the sustainability of the City of Glasgow. The yearly CO_2 emission reduction is around 11 200 tonnes. The yearly energy cost saving is 2.26 M€. Summing all of the smart solution energy savings gives a figure of some **37.2 GWh or around 0.48% of the annual energy consumption** in Glasgow of 7.6 TWh.

While the Rotterdam solutions have a large upscaling potential in Glasgow it should be noted that these also demand a low temperature grid, to supply the buildings with heat. However, Glasgow is to a large extent dependent on gas for heating purposes and does not have a large district heating network. Therefore, a smart thermal grid could be of interest for new establishments in the city, where in any case an investment in a new energy system has to be made. **By utilising waste streams, it is possible to supply many buildings with heat without exploiting primary resources for heat generation. Nevertheless, the increase in cost that this implies should not be foreseen.** With a transition of the electricity generation to more renewables, this might change, with lower electricity prices as a consequence.

Upscaling of G2 and G9, **battery-supported load management in high-rise flats is a lower hanging solution which would increase the thermal comfort of the buildings.** This is especially interesting as the price of batteries is going down.

4 Concluding discussion

Scaling of the demonstrated solutions in the RUGGEDISED project have in this deliverable been shown to have benefits to energy savings and CO_2 emissions. When scaling selected solutions, the analysis shows that an estimated 208 GWh of energy and 52 800 tonnes of CO_2 could be saved if the demonstrations were scaled to other parts of the cities.

However, there are some significant caveats regarding the likely energy savings. All the data for up-scaling of savings emerged from modelling work. All the modelling predictions are subject to uncertainty and similarly, all the scale-up parameters will also be subject to **uncertainty.** Moreover, modelling has been seen in the past to yield overly optimistic predictions of energy use (Menezes, Cripps, Bouchlaghem, & Buswell, 2012) and consequently the likelihood is that savings will be lower than those reported here.

Additionally, as has been shown in this deliverable, **the impact of scaling different measures will have very different results depending on the existing energy system**. For example, the energy, CO_2 and cost savings related to energy efficiency measures such as the energy management system U9 in Umeå and R8 in Rotterdam, have significantly different impact on both cost and CO_2 emissions due to both the difference in existing production and the number of buildings suited for the solution in the cities.

It should also be pointed out that not all the heat and electricity savings accrued from the smart solutions are directly comparable. For example, whilst the use of a battery and direct electric heat could result in energy savings of some 2 GWh per year in Glasgow tower block (this would reduce existing demand), the EV supported charging hub would act only to mitigate increased electrical demand from EVs, rather than reduce existing demand. So, strictly speaking these two demand reductions are **not cumulative**. Moreover, the Rotterdam heat recovery solutions indicate the heat available from low-grade sources that could result in savings only if connected to a heat load. This is different from **savings brought about from energy efficiency, which would directly reduce demand**. Again, it could be argued that not all the heat savings are cumulative. It should also be pointed out that the pavement heat collector solution, if implemented widely, would result in substantive disruption and civil works as large areas of pavement would need to be replaced.

Whilst this discussion has focused on energy it does not encompass other benefits that could accrue from the smart solutions: e.g. improved comfort from battery supported heating and encouraging the transition from fossil fuel to electric vehicles through the provision of charging hubs. And, **whilst the solutions only provide incremental improvements in energy performance, it is large numbers of incremental changes that will enable the city's sustainability goals to be achieved as opposed to quantum leaps.**

The scenarios in task 6.3 describes a plausible and relevant future and through this analysis there are now tangible and comparable numbers of the upscaling effects of the different solutions. This can now be used as input to the urban innovation platform to realise some of the upscaling potential.

ROTTERDAM . UMEÅ . GLASGOW

BRNO . PARMA . GDANSK

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6 Appendix - Figures

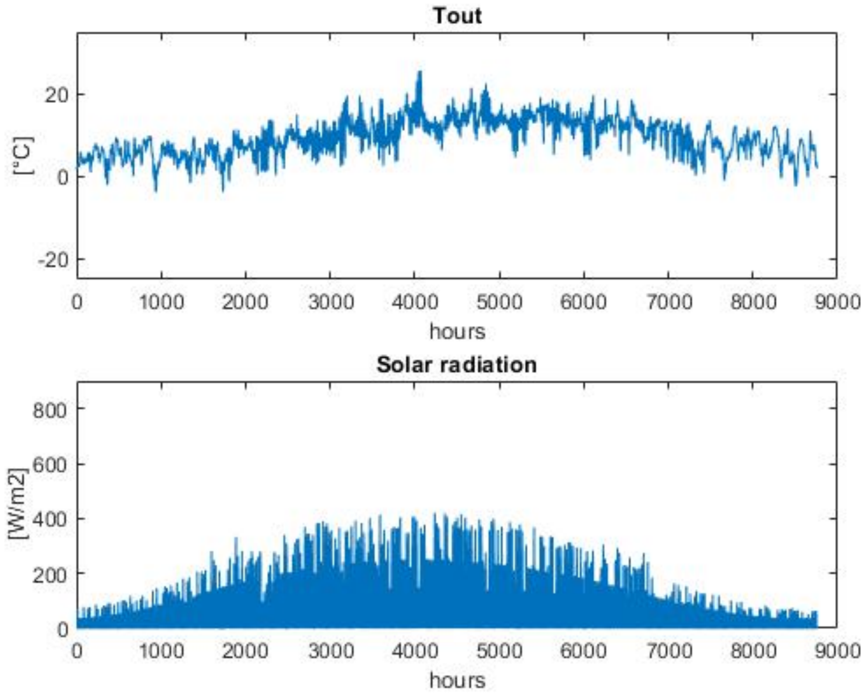

Figure 53. Temperature and solar radiation in Glasgow with hourly resolution.

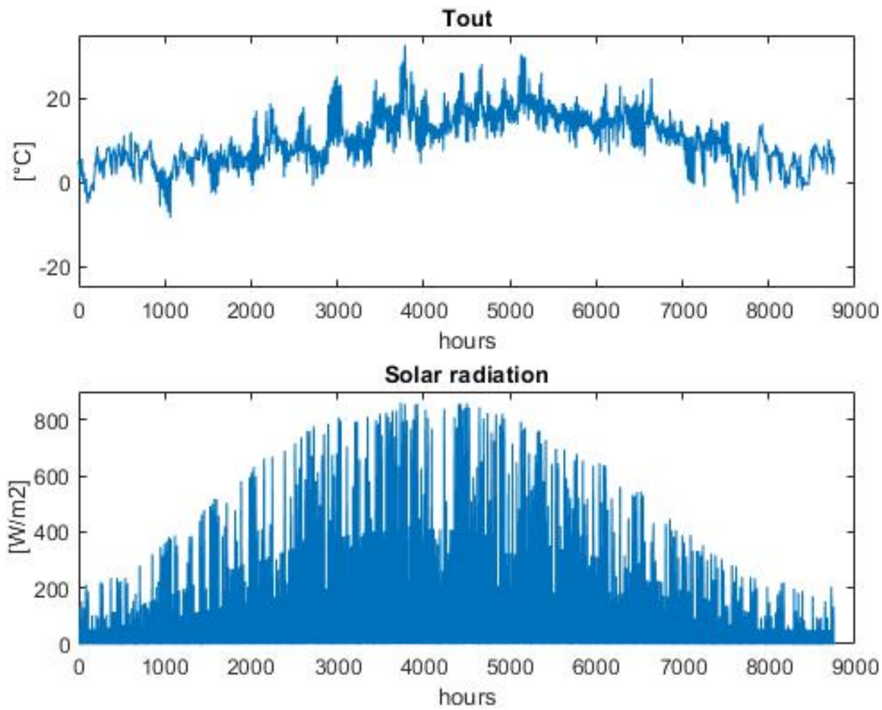

Figure 54. Temperature and solar radiation in Rotterdam with hourly resolution.

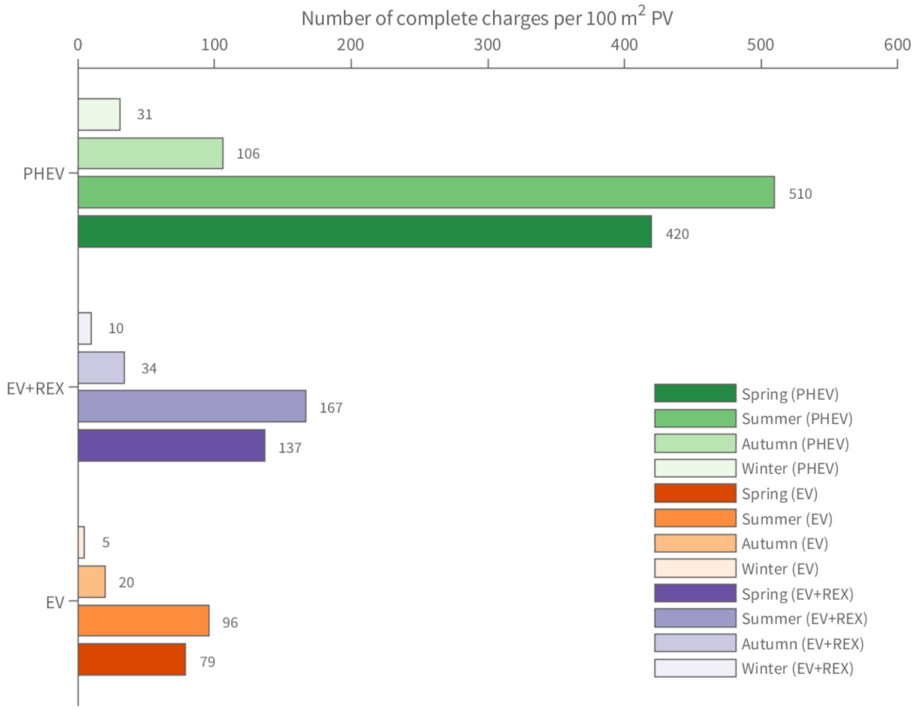

Figure 55: Number of complete charges per vehicle type per 100m^2 of PV in each season for Umeå.

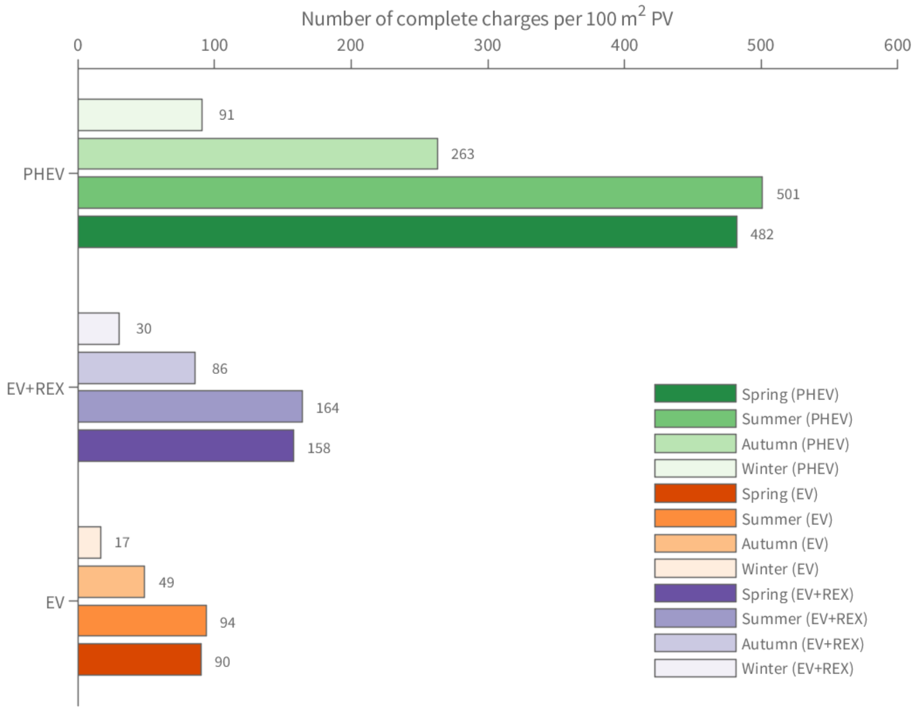

Figure 56: Number of complete charges per vehicle type per 100m^2 of PV in each season for Rotterdam.