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Industrial Electrical Engineering and Automation

Full Electrification of an extended Bus Route 20x in Lund

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1 Summary

In this report, and estimation of the costs related to a full electric operation of a bus route 20x, from Lund C to ESS, is made. The estimate is based on the report "Full electrification of Lund city buss traffic, a simulation study" written by Lars Lindgren at LTH, that do not cover route 20. Route 20x is an extended route 20, ending at ESS – a bit longer than today's route 20.

The extrapolation is based on an estimate on the transport needs in route 20x in 2030 and 2050, with 12 meter, 18,7 meter and 24 meter buses.

Three different charging systems are evaluated, two conductive charging systems and one inductive. One conductive version is commercial and represent current state of the art with only bus stop charging. The other conductive version is expected to be commercial in a few years and partly include dynamic charging (while the bus is moving, also called ERS – Electric Road System). The Inductive solution is also commercial and do also include partly dynamic charging.

Depending on the selection of energy supply system (Inductive or Conductive, ERS or No ERS) the additional investment cost for a full electric bus transport system between Lund C and ESS NE is 9 to 32 MSEK to cover for the transport capacity needed in 2030. The wide cost gap depends on selected charging technology and how heating of the buses is handled wintertime – with electric heating or a bio fuel based burner.

Note!, the additional investment ONLY covers the electro mobility related costs (batteries, charging systems, electric energy supply etc) and not the base line vehicle itself which is a combustion driven 12 meter Natural Gas bus. Road maintenance, bus garages or conventional vehicle maintenance is not included either since it is regarded as equal for a gas bus and an electric bus system.

The additional operational costs (i.e. Battery Cycling Cost, Electricity Cost, grid Connection fee, EV specific Maintenance Cost, Infrastructure Capital Cost and EV-specific Capital Cost) spans from 1.9 to 4.1 MSEK/year in 2030, to be compared to the 4,2 MSEK that the Natural Gas would cost if the same transport was solved with conventional buses.

The conclusions is that the operational cost of full electric buses on route 20x should be the same or lower than the costs of running natural gas buses in the same transport task.

IF the rest of the city bus transport system is also made electric, the synergies between route 20x and all other city bus routes become strong. The vehicles are interchangeable which boost redundancy and they can use the same workshop and night time charging resources.

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2 Background

During the academic year 2014/15 a study on a full electrification of Lund City bus routes was conducted and reported by Lars Lindgren at LTH in [1]. The study is made on the Bus Routes existing in May 2014 and do not include the later introduced Bus Route 20 in Lund.

This report estimates the cost of a fully electrified Bus Route 20, starting at Lund C and ending at Brunnshög in the same location as the end station of the corresponding Tram Line proposed.

This report is based on extrapolation of the results in [1] rather than redoing the optimization of the full electric public transport systems made in [1]. The reason is that the work in [1] is an extensive effort and the combination of interest in the outcome of a full electric bus solution for route 20x with resources to redo the job in [1] makes this extrapolation a good alternative.

Being an extrapolation, the results presented in this report do not have the same accuracy as those in [1], but they are still a good indicator of the investment costs and operational costs of a full electric bus line 20x.

3 Previous report summary

In [1], the differential cost of an EV based city bus system relative to the current natural gas based system is calculated. The costs accounted for are:

- The static charging stations with installation and connection to the power system.
- The dynamic charging strips (if any) and their connection to the power system.
- The on board energy storage (traction battery)
- The differential cost of an electric bus excluding battery relative to a natural gas bus.
- Three different assumptions on how heating is supplied wintertime.

The assumptions on both the vehicle cost and the traction battery cost are conservative and reality can be expected to develop towards lower costs than those assumed in the reference study.

The conclusions are that the differential cost of a full electric bus fleet on routes 1, 2, 3, 4, 5, 6, 9 and 21in Lund is somewhere between half and twice that of the cost of the natural gas supplied to the existing conventional natural gas buses.

The lowest cost is that of a system that allow using some dynamic charging strips of the type invented by Dan Zethreaus in Lund and currently being developed by LTH, and a separate (bio fuel based) heating system wintertime. The highest cost is based on only using static inductive or conductive charging solutions in combination with full electric heating system wintertime. The other solutions that end up in between these extremes, show similar cost levels as the current natural gas based transport system.

Accounting for expected future cost reduction on batteries and full electric vehicles and charging systems, a full electric bus fleet is likely to be very competitive based on cost only.

4 Route 20x assumptions

Bus route 20x represents a short extension of the current bus route 21. It starts at Lund C and ends at ESS, see Figure 4-1. Bus route 20x is modelled as 5.5 km long even though it is expected to be a little bit longer. 5.5 km is the expected tram route length. Later, within a few years, the route should become about 400 m shorter, following the construction of a new and more direct road system.

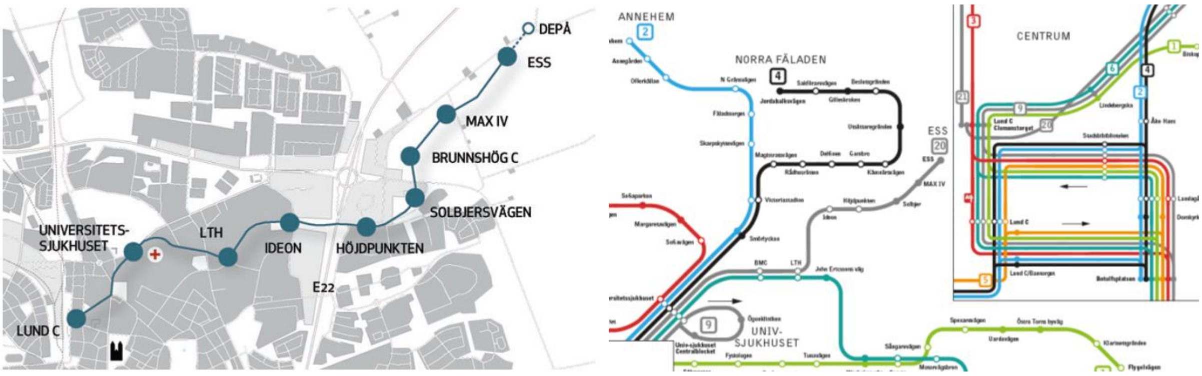

Figure 4-1 Proposed Tram Route (left) and Bus Route Line 20x (right)

4.1 Capacity requirements

The predicted capacity is summarized in Table 4-1.

Table 4-1 Predicted capacity requirements, travelers from Lund C towards Brunnshög [2].

Year	Total daily travellers	Peak hour travellers *22 % of Total Daily Travellers*
2013 (from Clemenstorget)	4 286	943
2030	8 486	1 867
2050	13 619	2 996

The transport solution is designed by the requirements during the peak hour. The following vehicles can be utilized:

- Bus 12 m 50 passengers
- Bus 18.7 meters 87 passengers
- Bus 24 meter 144 passengers
- Tram 32 meters 180 passengers

With the predicted capacity requirements from Table 4-1 and the vehicle alternatives above, it is possible to calculate the required departure intervals during peak hour. These are shown in Table 4-2.

Table 4-2 Estimated transport capacity as a function of vehicle capacity and Departure time interval for three different peak hour requirements. The **Blue field** covers the present situation. The Green field covers predicted requirements 2030 and the Yellow field covers the predicted requirements 2050.

The **Black frame** represents a 12 meter bus, the **Green Frame** represents an 18.7 meters Bus, the **Blue frame** a 24 meter (bi articulated) bus and the **Red frame** a 30 meter Tram.

Vehicle Capacity [passengers]	Departure interval [minutes]																		
	1	1,5	2	2,5	3	3,5	4	4,5	5	5,5	6	6,5	7	7,5	8	8,5	9	9,5	10
40	2400	1600	1200	960	800	686	600	533	480	436	400	369	343	320	300	282	267	253	240
50	3000	2000	1500	1200	1000	857	750	667	600	545	500	462	429	400	375	353	333	316	300
60	3600	2400	1800	1440	1200	1029	900	800	720	655	600	554	514	480	450	424	400	379	360
70	4200	2800	2100	1680	1400	1200	1050	933	840	764	700	646	600	560	525	494	467	442	420
80	4800	3200	2400	1920	1600	1371	1200	1067	960	873	800	738	686	640	600	565	533	505	480
90	5400	3600	2700	2160	1800	1543	1350	1200	1080	982	900	831	771	720	675	635	600	568	540
100	6000	4000	3000	2400	2000	1714	1500	1333	1200	1091	1000	923	857	800	750	706	667	632	600
110	6600	4400	3300	2640	2200	1886	1650	1467	1320	1200	1100	1015	943	880	825	776	733	695	660
120	7200	4800	3600	2880	2400	2057	1800	1600	1440	1309	1200	1108	1029	960	900	847	800	758	720
130	7800	5200	3900	3120	2600	2229	1950	1733	1560	1418	1300	1200	1114	1040	975	918	867	821	780
140	8400	5600	4200	3360	2800	2400	2100	1867	1680	1527	1400	1292	1200	1120	1050	988	933	884	840
150	9000	6000	4500	3600	3000	2571	2250	2000	1800	1636	1500	1385	1286	1200	1125	1059	1000	947	900
160	9600	6400	4800	3840	3200	2743	2400	2133	1920	1745	1600	1477	1371	1280	1200	1129	1067	1011	960
170	10200	6800	5100	4080	3400	2914	2550	2267	2040	1855	1700	1569	1457	1360	1275	1200	1133	1074	1020
180	**10800**	**7200**	**5400**	**4320**	**3600**	**3086**	**2700**	**2400**	2160	1964	1800	1662	1543	1440	1350	1271	1200	1137	1080

Transport capacity [passengers/hour]		
	943	*Current situation (2013)*
	1 867	*Predicted 2030*
	2 996	*Predicted 2050*

From Table 4-2 the following conclusions can be drawn:

1 **The 12 meter City Buses type** requires a 3 minute departure rate today, a 1.5 minute departure rate from 2030 and a 1 minute departure rate 2050.

2 IF **18.7 meter articulated** requires a 5.5 minute departure rate today, a 2.5 minute departure rate from 2030 and a 1.5 minute departure rate 2050.

3 IF **24 meter bi-articulated** requires a 8.5 minute departure rate today, a 4 minute departure rate from 2030 and a 2.5 minute departure rate 2050.

4 IF **Trams** requires a >10 minute departure rate today, a 5.5 minute departure rate from 2030 and a 3.5 minute departure rate 2050.

It is recognized that a departure interval shorter than 5 minutes may make the public transport solution sensitive to disturbances and that the departure interval never should be shorter than 2 minutes.

Based on these conclusions and the total round trip time, the number of vehicles required can be calculated as shown in Table 4-3, where the solutions giving longer departure intervals than 2 minutes are indicated with green fields.

Table 4-3 Number of vehicles needed depending on departure interval and vehicle capacity

Number of Vehicles needed						
		Round Trip time				
Vehicle type	**Departure Interval [minutes]**	26	28	30	32	34
12 m bus 2013	3	9	10	10	11	12
12 m bus 2030	1,5	**18**	19	20	22	23
12 m bus 2050	1	26	28	30	32	34
18.5 m bus 2013	5,5	5	6	6	6	7
18.5 m bus 2030	2,5	**11**	12	12	13	14
18.5 m bus 2050	1,5	18	19	20	22	23
24 m bus 2013	8,5	4	4	4	4	4
24 m bus 2030	4	**7**	7	8	8	9
24 m bus 2050	2,5	11	12	12	13	14
Tram 2013	10	3	3	3	4	4
Tram 2030	5,5	**5**	6	6	6	7
Tram 2050	3,5	**8**	8	9	10	10

From Table 4-3 the following conclusions are drawn:

1 The current 12 meter bus type is NOT sufficient to provide the transport needs by 2030 without too short departure intervals.

2 With 18.5 meter articulated buses the required transport requirements are provided up to 2030 with 11 buses and 2.5 minute departure intervals.

3 With 24 meter bi-articulated buses the required transport requirements are provided up to 2030 with 7 buses and 4 minute departure intervals.

4 With 30 meter trams the required transport requirements are provided up to 2030 with 5 trams and 5 minute departure intervals.

5 Cost estimation

A detailed cost estimation of bus route 20x requires an optimization of suitable locations for static charging points and optional dynamic charging strips as well as the on board battery storage in each vehicle.

Due to time restrictions, the intent with this report is NOT to do such an optimization. Instead it is assumed that bus route 20x is of the same nature as the other bus routes in Lund (1, 2, 3, 4, 5, 6, 9 and 21) and draws infrastructure and battery costs in roughly the same rate. Then the results of [1], see Table 5-1, can be used and extrapolated to include the estimated transport needed in route 20x.

Table 5-1 Summary of results from [1], including calculated costs per total daily kilometer driven.

	Conductive 1	Conductive 2		Inductive	
	No ERS	No ERS	ERS	No ERS	ERS
	Total Investment in Buses and Infrastructure [MSEK]				
No El heating	**109**	**64**	**46**	**134**	**127**
El heating 1	**306**	**142**	**78**	**307**	**219**
El heating 2	**140**	**89**	**62**	**225**	**169**
	Total Investment per bus-kilometer [kSEK/km]				
No El heating	*10,5*	*6,2*	*4,4*	*12,9*	*12,2*
El heating 1	*29,4*	*13,7*	*7,5*	*29,5*	*21,1*
El heating 2	*13,5*	*8,6*	*6,0*	*21,6*	*16,3*
	Yearly Extra Cost [MSEK/year]				
No El heating	**19**	**14**	**10,4**	**21**	**18,0**
El heating 1	**39**	**25**	**15**	**37**	**26**
El heating 2	**21,5**	**17,2**	**12,7**	**28,6**	**22**
	Yearly Cost per bus-kilometer [kSEK/km]				
No El heating	*1,80*	*1,30*	*1,00*	*1,98*	*1,73*
El heating 1	*3,79*	*2,37*	*1,41*	*3,53*	*2,50*
El heating 2	*2,07*	*1,65*	*1,22*	*2,75*	*2,12*

Table 5-1 is divided in 4 horizontal fields, two with **blue** text and two with **red** text, each with a set of data in **bold** letters and another set in *italic*. The two **bold** text fields show the Total Investment Cost in MSEK (Upper field) and the Annual Extra Cost in MSEK/year (lower field), both results from [1].

There are five different charging infrastructure alternatives (Conductive 1 & 2 + Inductive combined with three ways to handle the heating of the bus winter time). These are all described in detail in [1].

The **green** fields represent the selected cases used in the following analyses. Some additional considerations and assumptions are needed in the extrapolation:

1 An extension of the current road is needed to from todays to future end stations of route 20. The cost for this is expected to be 50 MSEK and is expected to have a lifetime of 50 years, i.e. 1 MSEK/year.

2 Articulated buses cost more than conventional 12 meter buses modelled in [1]. An articulated 18.5 meter and a Bi-Articulated 24 meter Diesel-bus today cost about 50 % and 100 % respectively more than a 12 meter electric city bus. These ratios are assumed to be the same in full electric versions.

3 The bigger buses will consume more energy and needs a bigger battery. The battery cost and energy consumption is expected to be proportional to the vehicle cost ratio vs a 12 meter bus.

4 A bus depot extension is needed to house the additional 13 buses needed in the 2030 scenario. The cost for these is estimated to 26 MSEK [3].

The scaling is based on the driven distance for city buses of Lund, with bus routes 1, 2, 3, 4, 5, 6, 9 and 21, which is 10400 km per day. The daily driven distance 2030 for bus route 20x is calculated in Table 5-2 and is 3102, 2046 and 1485 km with 12 m, 18.7 m and 24 meter buses respectively. The 12 meter bus requires a too short departure interval (1.5 minute) and is not suitable (see Table 4-3) 2030 but is included as reference.

Table 5-2 Estimated departure rates and driven distances in 2013, 2030 and 2050.

		Departure rate [#/hour]											
	Bus:	12m			18,7			24			Tram		
	Year:	2013	2030	2050	2013	2030	2050	2013	2030	2050	2013	2030	2050
Hour	Min departure rate [#/hour]	3	1,5	1	5,5	2,5	1,5	8,5	4	2,5	10	5,5	3,5
1	0	0	0	0	0	0	0	0	0	0	0	0	0
2	0	0	0	0	0	0	0	0	0	0	0	0	0
3	0	0	0	0	0	0	0	0	0	0	0	0	0
4	0	0	0	0	0	0	0	0	0	0	0	0	0
5	2	2	2	2	2	2	2	2	2	2	2	2	2
6	6	15	30	45	9	18	30	6	12	18	5	5	5
7	8	20	40	60	11	24	40	8	15	24	6	11	18
8	6	15	30	45	9	18	30	6	12	18	5	5	5
9	4	4	4	4	4	4	4	4	4	4	4	4	4
10	4	4	4	4	4	4	4	4	4	4	4	4	4
11	4	4	4	4	4	4	4	4	4	4	4	4	4
12	4	4	4	4	4	4	4	4	4	4	4	4	4
13	4	4	4	4	4	4	4	4	4	4	4	4	4
14	6	15	30	45	9	18	30	6	12	18	5	5	5
15	8	20	40	60	11	24	40	8	15	24	6	11	18
16	8	20	40	60	11	24	40	8	15	24	6	11	18
17	6	15	30	45	9	18	30	6	12	18	5	5	5
18	4	4	4	4	4	4	4	4	4	4	4	4	4
19	4	4	4	4	4	4	4	4	4	4	4	4	4
20	4	4	4	4	4	4	4	4	4	4	4	4	4
21	2	2	2	2	2	2	2	2	2	2	2	2	2
22	2	2	2	2	2	2	2	2	2	2	2	2	2
23	2	2	2	2	2	2	2	2	2	2	2	2	2
24	2	2	2	2	2	2	2	2	2	2	2	2	2
Achieved Daily Capacity		8 100	14 100	20 100	9 657	16 182	24 534	12 960	19 440	26 784	14 400	17 100	20 880
Required Capcity:		*4 286*	*8 486*	*13 619*	*4 286*	*8 486*	*13 619*	*4 286*	*8 486*	*13 619*	*4 286*	*8 486*	*13 619*

	Total Daily Distance [km]											
Bus:	12m			18,7			24			Tram		
Hour / Year:	2013	2030	2050	2013	2030	2050	2013	2030	2050	2013	2030	2050
1	0	0	0	0	0	0	0	0	0	0	0	0
2	0	0	0	0	0	0	0	0	0	0	0	0
3	0	0	0	0	0	0	0	0	0	0	0	0
4	0	0	0	0	0	0	0	0	0	0	0	0
5	22	22	22	22	22	22	22	22	22	22	22	22
6	165	330	495	99	198	330	66	132	198	55	55	55
7	220	440	660	121	264	440	88	165	264	66	121	198
8	165	330	495	99	198	330	66	132	198	55	55	55
9	44	44	44	44	44	44	44	44	44	44	44	44
10	44	44	44	44	44	44	44	44	44	44	44	44
11	44	44	44	44	44	44	44	44	44	44	44	44
12	44	44	44	44	44	44	44	44	44	44	44	44
13	44	44	44	44	44	44	44	44	44	44	44	44
14	165	330	495	99	198	330	66	132	198	55	55	55
15	220	440	660	121	264	440	88	165	264	66	121	198
16	220	440	660	121	264	440	88	165	264	66	121	198
17	165	330	495	99	198	330	66	132	198	55	55	55
18	44	44	44	44	44	44	44	44	44	44	44	44
19	44	44	44	44	44	44	44	44	44	44	44	44
20	44	44	44	44	44	44	44	44	44	44	44	44
21	22	22	22	22	22	22	22	22	22	22	22	22
22	22	22	22	22	22	22	22	22	22	22	22	22
23	22	22	22	22	22	22	22	22	22	22	22	22
24	22	22	22	22	22	22	22	22	22	22	22	22
Achieved Daily Capacity	**1782**	**3102**	**4422**	**1221**	**2046**	**3102**	**990**	**1485**	**2046**	**880**	**1045**	**1276**

The additional investment and annual costs for running full EV buses on route 20x are thus estimated in Table 5-3 and Table 5-4.

Table 5-3 Estimated investment cost based on extrapolated daily bus driving distance. Road extension and Bus garage is NOT included!

	Total ADDITIONAL Investment in Buses & Infrastructure 2030 [MSEK]		
Bus size:	*12m*	*18,7*	*24*
Cond1, El Heat 2, No ERS	42	27	18
Cond2, No El Heat, ERS	14	9	6
Ind, El Heat 2, ERS	50	32	22

Table 5-4 Additional annual Costs for full EV buses on route 20x = the equivalent of Gas Buses Fuel Costs.

	Yearly Additional Cost for Electric Transport [MSEK]		
Bus size:	*12m*	*18,7*	*24*
Cond1, El Heat 2, No ERS	6,4	4,0	2,7
Cond2, No El Heat, ERS	3,1	1,9	1,2
Ind, El Heat 2, ERS	6,6	4,1	2,6
Ref: Natural Gas Cost	*6,3*	*4,2*	*3,0*

In addition to the figures in Table 5-3 and Table 5-4, the cost for extending the road for the bus route should be accounted for, estimated to 50 MSEK, and a bus garage, estimated to 26 MSEK.

6 Conclusion

Depending on the selection of energy supply system (Inductive or Conductive, ERS or No ERS) the additional investment cost for a full electric bus transport system between Lund C and Brunnshög NE is 9 and 32 MSEK to cover for the transport capacity needed in 2030. The wide cost gap depends on selected charging technology.

Note!, the additional investment ONLY covers the electro mobility related costs (batteries, charging systems, electric energy etc) and not the base line which is a combustion driven Natural Gas bus.

The additional operational costs (i.e. Battery Cycling Cost, Electricity Cost, grid Connection fee, Maintenance, Infrastructure Capital Cost and EV-specific Capital Cost) spans from 1.9 to 4.1 MSE/year in 2030, to be compared to the 4,2 MSEK that the Natural Gas would cost if the same transport was solved with conventional buses.

The conclusion is that using 18,7 meter articulated Full Electric Buses will require an additional investment up to 32 MSEK to cover the costs specific for electric buses and the annual costs for these are equal to or less than the costs for the natural gas required to drive conventional buses.

It should be noted that the method used in this short report, to extrapolate the detailed cost estimate of a full electric city transport in Lund, probably is a bit pessimistic. It is likely that the charging infrastructure on route 20x is relatively cheaper compared to the rest of Lund as modelled in [1], since the traffic intensity is higher thus sharing the infrastructure cost on more vehicles. Extrapolation do not account for that sharing. Another benefit for route 20x is that IF the other bus routes in Lund were made electric like described in [1], route 20x would benefit from using exactly the same vehicle types thus reducing the total needs for spare bus capacity.

7 References

1) Lindgren, L. “Full electrification of Lund city buss traffic, a simulation study”, Industrial Electrical Engineering and Automation, LTH, Maj 2015.
2) Hed, B. ”Kan befintliga busslinjer utnyttjas bättre?”, Aktion för Spårvägsfritt Lund, 2013-10-23.
3) Gustafsson, Ulf. Personlig kommunikation.