OPTIMIZATION OF THE MAIN FANS AND ASSOCIATED DRIVES FOR THE E4 STOCKHOLM BYPASS

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ABSTRACT

The Stockholm Bypass project is part of the European motorway E4 and will connect the southern and northern regions of the Stockholm County. The Bypass is 21 km long, of which 18 km are in tunnels.

The ventilation system of the unidirectional tunnel consists of 241 jet fans (124 x 1000 N and 117 x 1500 N) and 47 main axial fans rated at 200 m³/s, installed in 17 ventilation stations. Minimising environmental impact is a key objective of the Swedish Transport Administration (Trafikverket). The total installed fan power amounts to 27 MW (17 MW for the main axial fans and 10 MW for the jet fans). Optimising fan and drive efficiency as well as minimising flow losses are therefore essential.

Eighteen of the 47 main axial fans must provide 120 m³/s in reverse-flow mode (60% reversibility), while the remaining 29 are operated only in forward direction. Pressure losses and ventilation regimes vary among the 17 ventilation stations. For system-redundancy reasons, all 47 motor-impeller units are required to be identical.

The paper discusses:

- design requirements for the axial fans and the resulting main design parameters
- duty points for the ventilation stations and for the axial fans
- evaluation of three variable-speed configurations:
    - A: variable speed drive (VSD),
    - B: two-speed 50% / 100 % (6/12-pole)
    - C: two-speed 75% / 100 % (6/8-pole).
- analysis of the performance of ventilation stations operating at 20 % to 100 % capacity
- evaluation for five typical operating scenarios to determine the most energy-efficient configuration

The study concludes that the intended configuration i.e. axial fans with variable pitch in motion combined with variable speed drives offers the highest overall energy efficiency. Only in one scenario is variant C marginally more efficient.

Keywords: Variable pitch in motion, axial fans, variable speed drives, two-speed motors

1. INTRODUCTION

The Stockholm Bypass project (Förbifahrt Stockholm) is part of the European motorway E4 and will connect the southern and northern regions of the Stockholm County. The bypass is 21 km long of which 18 km are in tunnels.

The unidirectional tunnel applies longitudinal ventilation with air-exchange stations. The ventilation system comprises 241 jet fans (124 x 1000 N with shaft power of 37 kW and 117 x 1500 N with shaft power of 45 kW) as well as 47 main axial fans with a nominal volume flow of 200 m³/s (46 fans at 355 kW and one at 75 kW[1]) installed in 17 ventilation stations. The total installed shaft power is 26,258 kW.

The specifications of the axial fans include:

- variable pitch in motion enabling reverse-flow operation
- design volume flow: Q =200 m³/s per fan (in forward direction)
- reverse volume flow: Q=120m³/s (60% of forward design flow)
- variable-speed drive operation
- suitable for parallel operation including start-up
- identical motor-impeller units for all stations
- installed motor shaft power: 355 kW
- certification for operation at 200°C for 120 minutes

An overview of the ventilation stations is provided in Table 1.

Table 1: Ventilation stations

Fan station	Type	Number installed fans	Number fans in operation
271	Exhaust	1	1
272	Exhaust	3	3
279	Exhaust	3 + 1 (redundant)	3
371	Exhaust	3	3
372	Exhaust/Supply	3	3
373	Exhaust/Supply	3	3
374	Exhaust	3	3
375	Exhaust	3	3
376	Exhaust/Supply	3	3
377	Exhaust/Supply	3	3
378	Exhaust	3	3
471	Exhaust	3	3
472	Exhaust/Supply	3	3
473	Exhaust/Supply	3	3
474	Exhaust	3	3
475*	Low-pressure shaft fan	1	1
571	Exhaust	3	3

*Special fan, which is not involved in this study

[1] The single 75 kW exhaust fan is a low-pressure shaft fan and is not considered in this analysis

2. OBJECTIVE OF THE STUDY

A key design criterion for the Stockholm Bypass ventilation system was to minimise power consumption. This raised the following question:

Are alternative fan–motor configurations feasible that eliminate the need for variable speed drives and thereby avoid converter-related losses?

To answer this question, the electrical power requirement had to be calculated for each configuration, taking into account the expected operating durations under various scenarios.

3. PRECONDITIONS

The fan selection was based on the following criteria:

a. The blade profile must be fully or partly reversible.
b. The fan diameter must be suitable for all required duty points (see Figure 1, Figure 2).
c. The hub diameter must be optimised for the required pressure rise and large enough to house the electric motor.
d. The number of blades must be optimised for pressure rise and maximum efficiency.
e. Identical motor-impeller units must be used in all ventilation stations.
f. Pressure losses across the complete fan unit must be minimised.
g. The maximum motor speed is determined by the pole number of a 50 Hz electric motor.

Figure 1 shows the required duty points for the fan stations:

- up to 200 m³/s with one fan in operation
- up to 600 m³/s with three fans in operation
- reverse extraction of at least –360 m³/s with three fans in operation

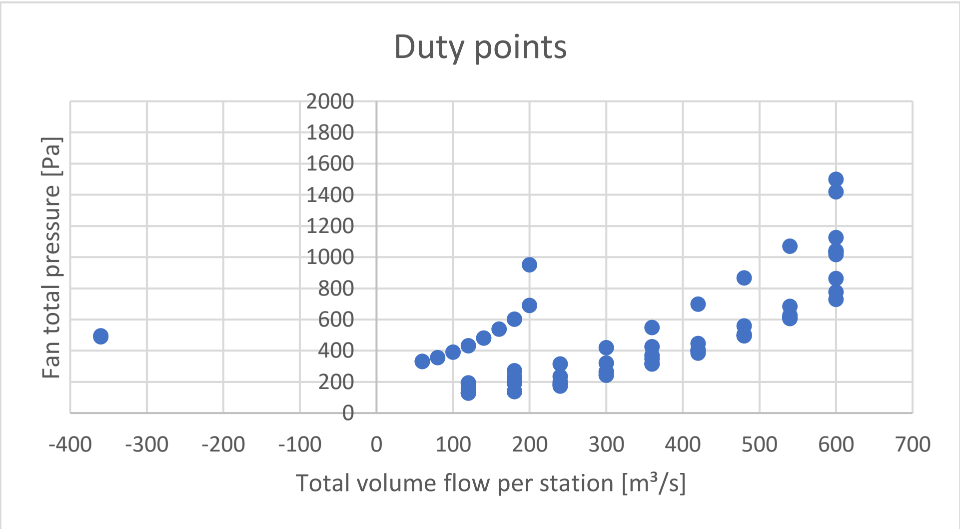

Figure 1: Duty points for the ventilation stations. For one fan up to 200 m^3/s and with three fans up to 600 m^3/s. Reversing three fans, the extraction capacity shall be at least -360 m^3/s.

These station-level requirements translate into the fan duty points shown in Figure 2.

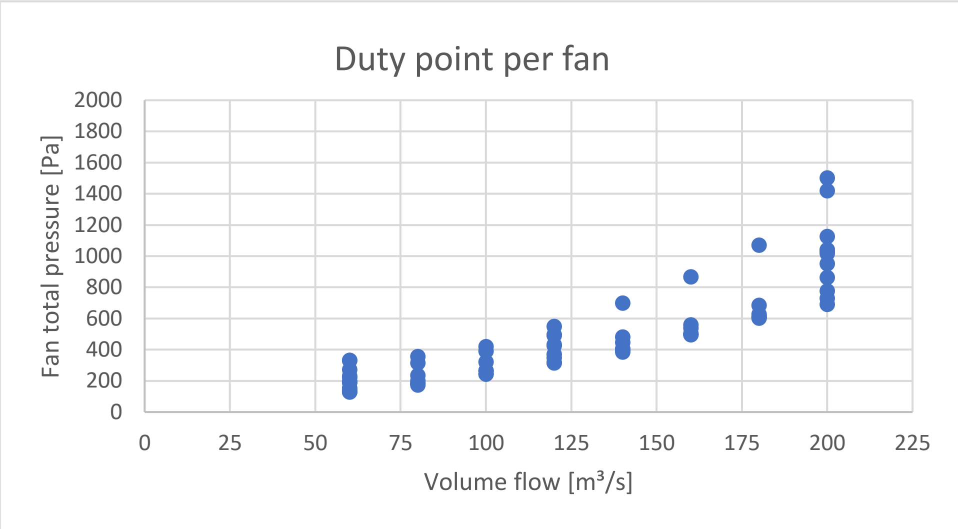

Figure 2: Fan duty points

4. INVESTIGATED VARIANTS

The optimal fan design (impeller diameter, hub diameter, blade count, and variable pitch in motion) was assumed fixed. Only the motor-speed configurations were varied:

- Variant A: fan with a variable speed drive (frequency converter)
- Variant B: fan with a Dahlander 6/12-pole motor (995/497 min^{-1})
- Variant C: fan with a 6/8-pole motor (995/746 min^{-1})
- Variant D: fan with a 6/10-poles motor (995/597 min^{-1})

Five operating scenarios were used to evaluate the total energy consumption (see section 4.6).

4.1. Required input

To calculate the electrical power demand, the following data were required for each duty point:

a. Blade angle
b. Aerodynamic fan efficiency
c. Fan rotational speed
d. Motor efficiency at the corresponding speed
e. For Variant A: variable speed drive efficiency

4.2. Variant A: Input Data

Variant A assumes a 355 kW, 6-pole motor (ABB M3BPW 355LKB 6) with a nominal speed of 995 rpm. The fan performance and motor efficiency characteristics are shown in Figure 3.

The variable speed drive efficiency as a function of torque is given in Table 2.

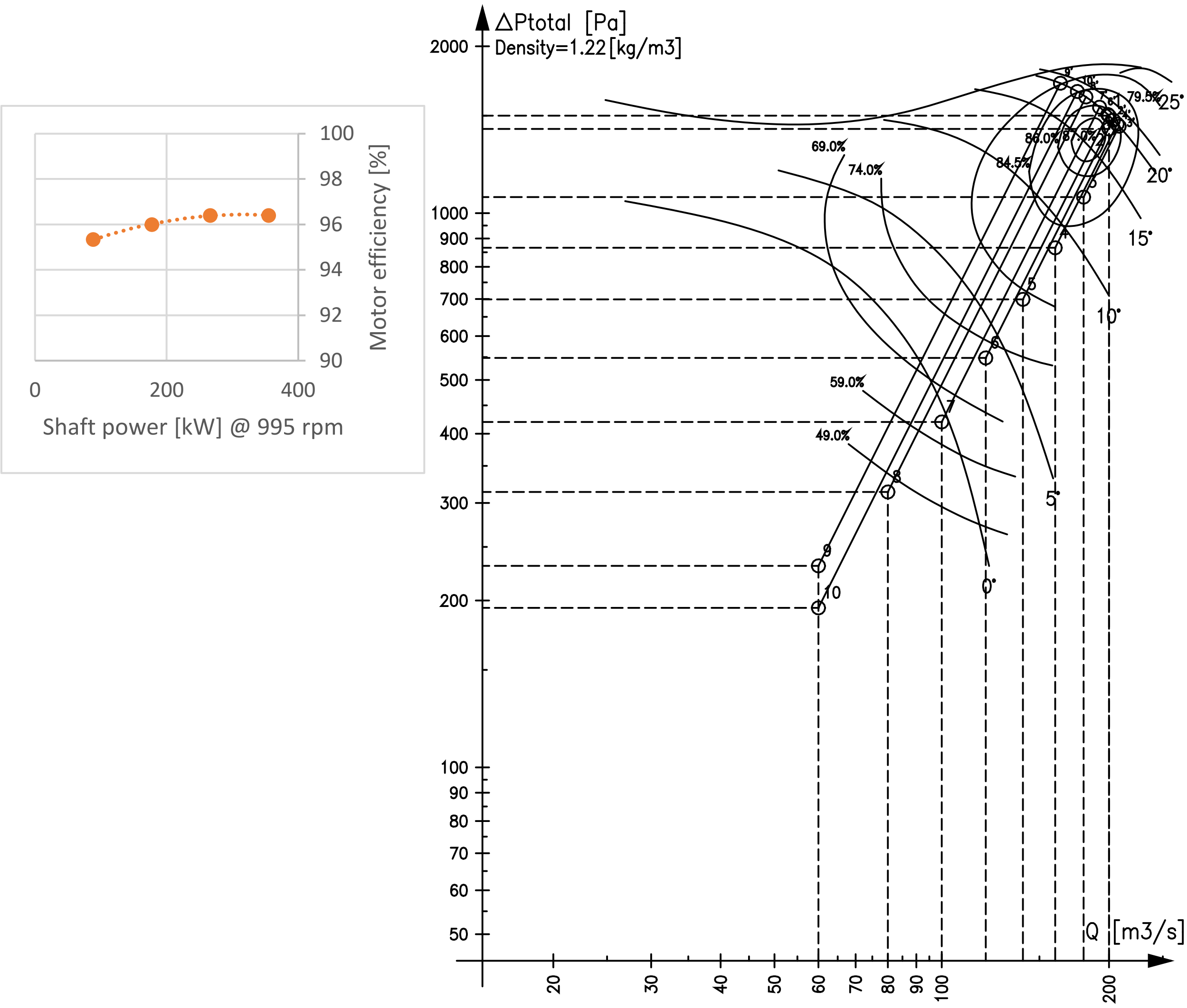

Figure 3: Variant A. Right: Fan curve. Left: Motor efficiency at full speed.

Table 2: Variant A: Efficiency of variable speed drive (frequency converter) including filters etc.

	Frequency converter together with harmonic filter, DU/DT filter, DC trottle										
Efficiency [%]	Speed [%]										
Torque [%]	0%	10%	20%	30%	40%	50%	60%	70%	80%	90%	100%
100%				97,67	97,68	97,68	97,70	97,69	97,69	97,67	97,67
90%				97,67	97,67	97,67	97,67	97,67	97,67	97,67	97,67
80%				97,67	97,67	97,67	97,67	97,67	97,67	97,67	97,67
70%				97,66	97,66	97,66	97,66	97,66	97,66	97,66	97,66
60%				97,63	97,63	97,63	97,63	97,63	97,63	97,63	97,63
50%				97,55	97,55	97,55	97,55	97,55	97,55	97,55	97,55
40%				97,39	97,39	97,39	97,39	97,39	97,39	97,39	97,39
30%				97,10	97,10	97,10	97,10	97,10	97,10	97,10	97,10
20%				96,51	96,51	96,51	96,51	96,51	96,51	96,51	96,51
10%				95,07	95,07	95,07	95,07	95,07	95,07	95,07	95,07
0%				88,75	88,75	88,75	88,75	88,75	88,75	88,75	88,75

4.3. Variant B: Input data

Variant B uses a 355 kW Dahlander 6/12-pole motor (ABB M3BPW 400LD 6G), capable of operating at full and half speed.

Fan performance and motor efficiency curves are shown in Figure 4.

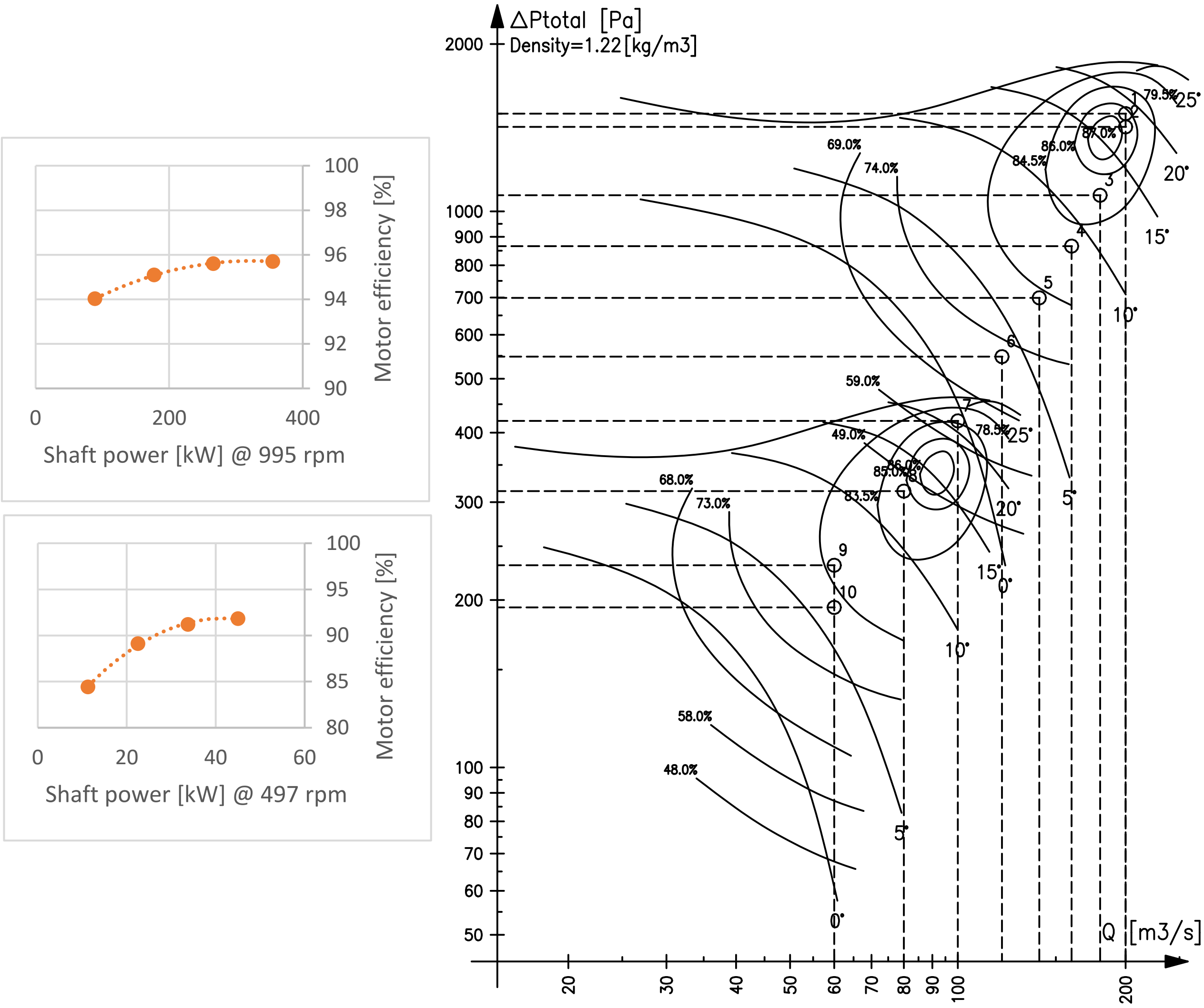

Figure 4: Variant B. Right: Fan curve.
Left: Motor efficiency at full speed (top) and at half speed (bottom)

4.4. Variant C: Input data

Variant C uses a 355 kW, 6/8-pole motor (ABB M3BP 400LB 6/8), providing 100% and 75% operating speeds.

Fan performance and motor efficiency curves are shown in Figure 5.

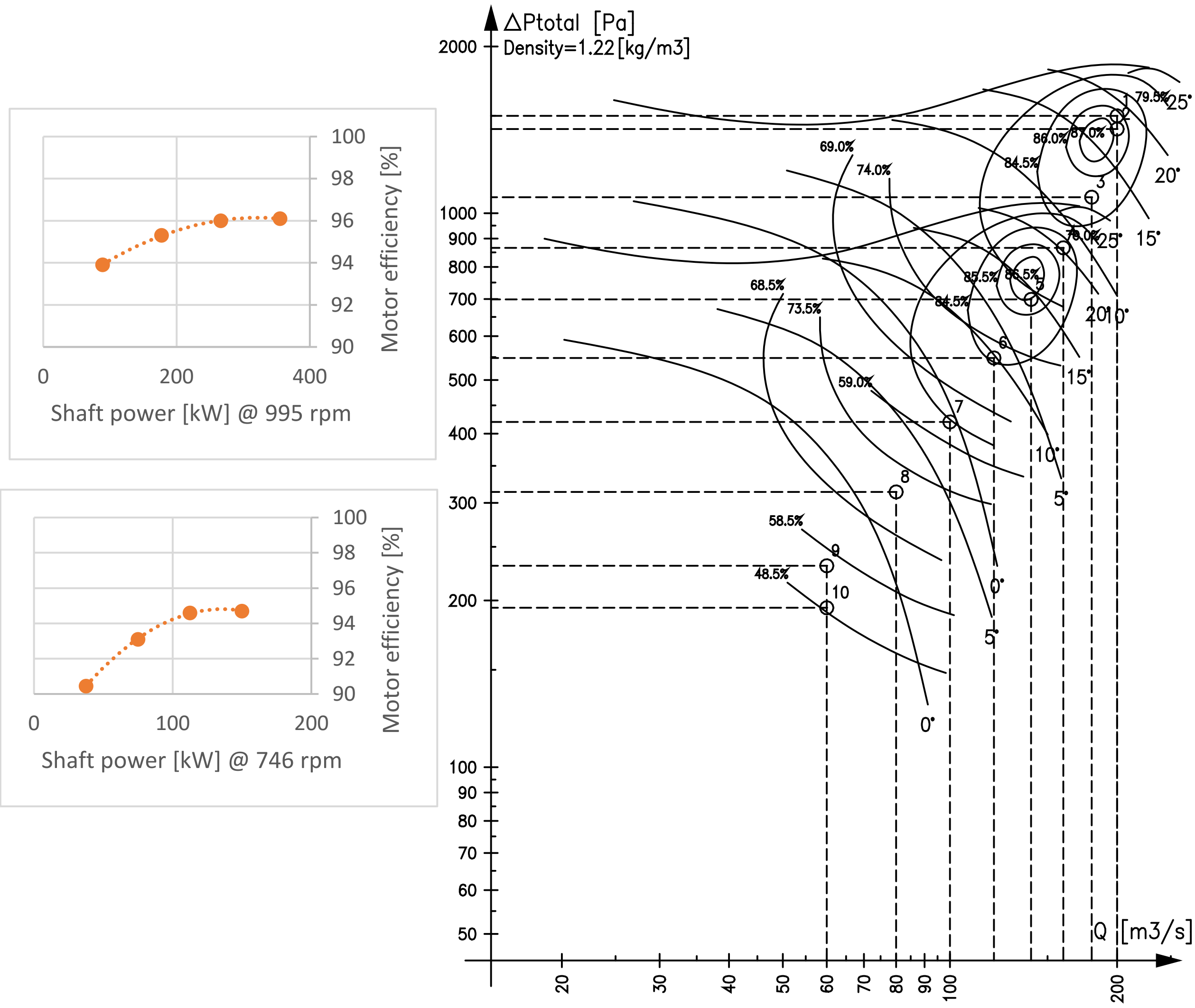

Figure 5: Variant C. Right: Fan curve.
Left: Motor efficiency at full speed (top) and at 75% speed (bottom)

4.5. Variant D: exclusion

During the study, it became clear that a dual-winding motor capable of 995 and 597 rpm would require a larger frame size than could be accommodated in the fan hub. Variant D was therefore excluded from further analysis.

4.6. Operating scenarios

Extensive simulations were used to define five representative operating scenarios for the calculations of operating costs.

Table **3** provides an overview. One station (279) is dedicated to smoke extraction and was therefore assigned only 0.01 daily operating hours.

Table 3: Five investigated operation scenarios. One fan station (279) is dedicated to smoke extraction, which therefore has been estimated to merely have 0.01 daily running hour.

Ventilation station capacity	Fan flow rate [m3/s]	Fans operating	Daily running hours				
			Scenario I	Scenario II	Scenario III	Scenario IV	Scenario V
100%, Smoke extraction	200	3	0.01	0.01	0.01	0.01	0.01
100%	200	3	0.01	1.00	0.00	0.00	1.00
90%	180	3	0.50	1.00	0.00	0.00	2.00
80%	160	3	1.00	1.00	0.50	0.50	2.00
70%	140	3	1.00	1.00	1.00	1.00	1.00
60%	120	3	1.50	1.00	1.50	4.00	0.50
50%	100	3	2.00	1.00	2.00	1.00	0.00
40%	80	3	2.50	1.00	2.50	0.50	0.00
30%	60	3	2.50	1.00	3.00	0.00	0.00
20%	60	2	1.00	1.00	3.50	0.00	0.00

5. RESULTS

Intermediate results for station 378 are presented below, as this station is representative of the stations 371, 374, 375, 471, and 474. Subsequently, aggregated results for all stations are summarised.

5.1. Intermediate results of fan station 378

The results for the three variants and their respective power consumption are shown below, see Table 4, Table 5 and Table 6.

Table 4: Variant A

VARIANT A (n=995min^{-1} with VSD)												
Operation percentage			100%	100%	90%	80%	70%	60%	50%	40%	30%	20%
Volume flow per fan	Q_{Fan}	[m³/s]	200	200	180	160	140	120	100	80	60	60
Total pressure loss	Δp_{total}	[Pa]	1126	863	684	558	446	426	321	235	271	190
Motor speed	n	[Min^{-1}]	995	923	826	740	656	606	517	431	417	365
Fan Efficiency	η_{Fan}	[%]	85.4%	81.9%	81.1%	81.5%	81.7%	84.2%	85.0%	85.8%	78.1%	84.4%
Shaft power	P_{shaft}	[kW]	263.7	210.7	151.8	109.5	76.4	60.7	37.8	21.9	20.8	13.5
Electrical power	$P_{elektric}$	[kW]	273.8	219.1	158.2	114.6	80.4	64.1	40.4	24.0	22.9	15.4
Motor efficiency	η_{motor}	[%]	96.3%	96.2%	95.9%	95.6%	95.1%	94.7%	93.4%	91.1%	90.9%	87.9%
Frequency Converter Efficiency	η_{VSD}	[%]	97.4%	97.4%	97.3%	97.2%	96.9%	96.8%	96.3%	95.4%	95.3%	94.3%
Electrical power	P_{grid}	[kW]	281.1	225.1	162.7	117.9	82.9	66.2	42.0	25.2	24.0	16.3
Total efficiency	η_{total}	[%]	80.1%	76.7%	75.7%	75.7%	75.3%	77.2%	76.5%	74.6%	67.6%	70.0%

Table 5: Variant B

VARIANT B (n=995/497min^{-1})												
Operation percentage			100%	100%	90%	80%	70%	60%	50%	40%	30%	20%
Volume flow per fan	Q_{Fan}	[m³/s]	200	200	180	160	140	120	100	80	60	60
Total pressure loss	Δp_{total}	[Pa]	1126	863	684	558	446	426	321	235	271	190
Motor speed	n	[Min^{-1}]	995	995	995	995	995	995	497	497	497	497
Fan Efficiency	η_{Fan}	[%]	85.4%	81.5%	80.0%	75.5%	71.0%	69.0%	85.4%	78.0%	80.0%	77.0%
Shaft power	P_{shaft}	[kW]	263.7	211.8	153.9	118.3	87.9	74.1	37.6	24.1	20.3	14.8
Electrical power	$P_{elektric}$	[kW]	276.1	222.1	162.0	125.0	93.6	79.2	41.1	26.9	22.9	17.1
Motor efficiency	η_{motor}	[%]	95.5%	95.3%	95.0%	94.6%	94.0%	93.6%	91.4%	89.6%	88.7%	86.7%
Total efficiency	η_{total}	[%]	81.6%	77.7%	76.0%	71.4%	66.7%	64.6%	78.0%	69.9%	71.0%	66.7%

Table 6: Variant C

VARIANT C (n=995/746min^{-1})												
Operation percentage			100%	100%	90%	80%	70%	60%	50%	40%	30%	20%
Volume flow per fan	Q_{Fan}	[m³/s]	200	200	180	160	140	120	100	80	60	60
Total pressure loss	Δp_{total}	[Pa]	1126	863	684	558	446	426	321	235	271	190
Motor speed	n	[Min^{-1}]	995	995	995	746	746	746	746	746	746	746
Fan Efficiency	η_{Fan}	[%]	85.4%	81.5%	80.0%	79.5%	80.5%	81.5%	80.5%	74.5%	64.0%	63.0%
Shaft power	P_{shaft}	[kW]	263.7	211.8	153.9	112.3	77.6	62.7	39.9	25.2	25.4	18.1
Electrical power	$P_{elektric}$	[kW]	276.1	222.1	162.0	120.1	83.4	67.7	43.5	28.0	28.2	20.4
Motor efficiency	η_{motor}	[%]	95.5%	95.3%	95.0%	93.5%	93.0%	92.7%	91.7%	90.2%	90.3%	88.7%
Total efficiency	η_{total}	[%]	81.6%	77.7%	76.0%	74.3%	74.9%	75.6%	73.8%	67.2%	57.8%	55.8%

5.2. Average efficiency

The average efficiency at each duty point - expressed as a percentage of volume flow - was calculated for all three variants and is shown in Figure 6.

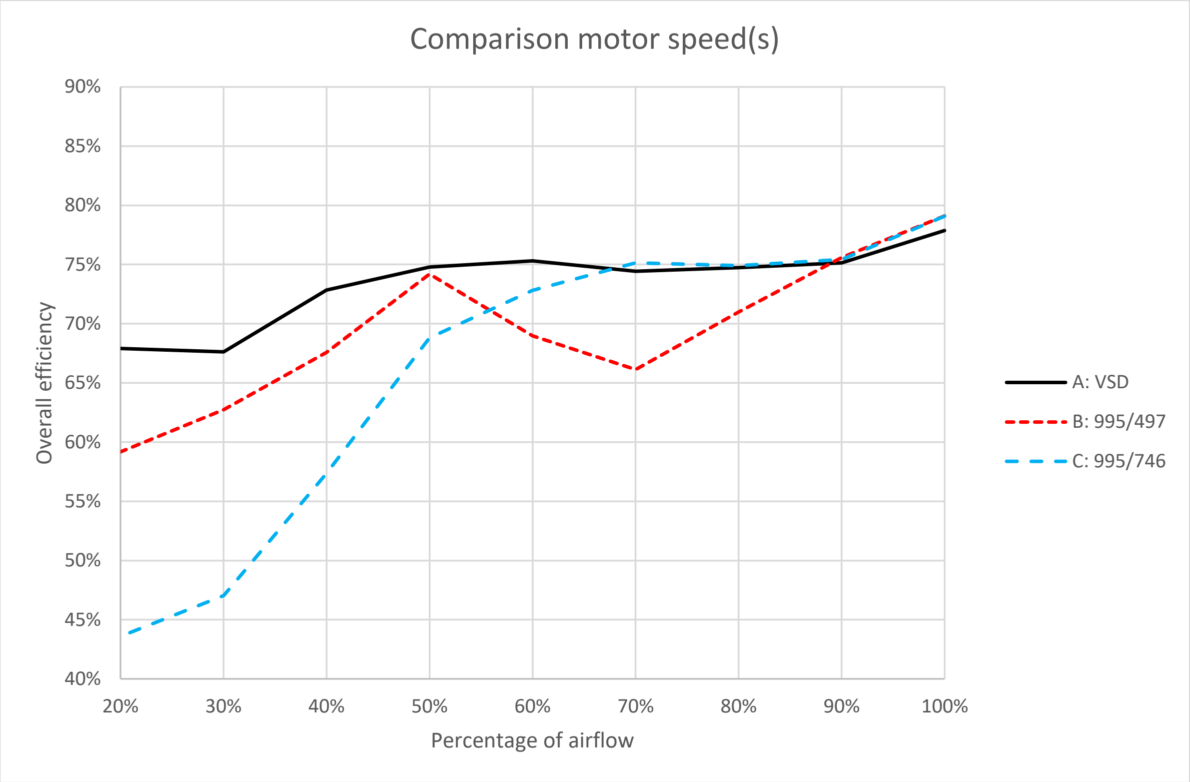

Figure 6: Comparison of efficiencies.

5.3. Annual power consumption

Annual energy demand was determined for each of the five operating scenarios (see Table 7), based on 310 operating days per year.

For comparison, Table 8 shows normalised values with 100% representing the most efficient variant for that particular scenario.

Table 7: Annual power consumption

Annual power consumption [kWh]			
	A: VSD	B: 995/497	C: 995/746
Scenario I	7 355 336	7 707 587	8 036 087
Scenario II	9 781 387	10 027 169	10 053 042
Scenario III	5 983 929	6 323 438	6 909 141
Scenario IV	5 651 667	6 127 297	5 853 981
Scenario V	11 776 474	12 043 032	11 705 719

Except for scenario V, Variant A with a VSD is the most energy-efficient solution.

The Dahlander configuration (Variant B) consistently exhibits the highest energy consumption.

Only in one scenario is Variant C marginally more efficient than Variant A.

Table 8: Normalised annual power consumption per scenario

Annual power consumption percentage [%]			
	A: VSD	B: 995/497	C: 995/746
Scenario I	100.00%	104.79%	109.26%
Scenario II	100.00%	102.51%	102.78%
Scenario III	100.00%	105.67%	115.46%
Scenario IV	100.00%	108.42%	103.58%
Scenario V	100.60%	102.88%	100.00%
Average	100.12%	104.85%	106.22%

6. CONCLUSIONS

For the Stockholm Bypass project, the following conclusions can be drawn:

- Fans operated via a variable speed drive (VSD) are slightly less efficient at maximum speed than fans with two-speed motors.
- However, when reduced speed is required, VSD-driven fans generally achieve significantly higher overall efficiency.
- Under typical operating conditions and expected yearly operating hours, the VSD solution is the most energy-efficient configuration.
- Only if the fans are expected to operate for many hours at maximum operation point may a two-speed configuration become more efficient.
- The originally planned configuration - axial fans with variable pitch in motion combined with variable speed drives - was confirmed to be the optimal solution.