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ASSESSMENT OF ENERGY PRODUCTION AND WAKE LOSSES FOR MOLDALSKNUTEN WIND FARM

1 Background

Norsk Vind AS (the Client) are currently developing Moldalsknuten wind farm, located in a mountainous area in Sokndal municipality in Rogaland County. The Moldalsknuten planning area is located inside the existing Tellenes wind farm, which is located in both Sokndal and Lund municipalities. Tellenes wind farm was commissioned in 2017 with 50 Siemens S113-3.2MW turbines with 92.5 m hub height (see Figure 1).

The expected energy production from Tellenes wind farm has been estimated with and without the potential construction of Moldalsknuten wind farm, with separate estimates for the turbines within each of the two municipalities to facilitate a calculation of the potential changes in production tax that can be expected.

The expected energy production for the planned turbines at Moldalsknuten are presented as well, along with an evaluation of the external wake impact that the planned and existing turbines at Tellenes will have on each other.

The assessment is based primarily on a Moldalsknuten wind resource assessment and expected energy production report from August 2016 [1], with the results validated using 6 years of aggregated production data from the Tellenes wind farm [3]. The wind data consisted of four 50 m measurement masts installed within the Tellenes wind farm area in 2005/2006, three with 2 years and 1 mast with 9.5 years of data. The data analysis and assumptions from the 2016 report were for the most part used for this assessment without adjustment.

The measurement masts and 2km distance circles (general limit of representativeness of a mast in complex terrain) are presented in Figure 1, together with the 50 existing turbines at Tellenes wind farm.

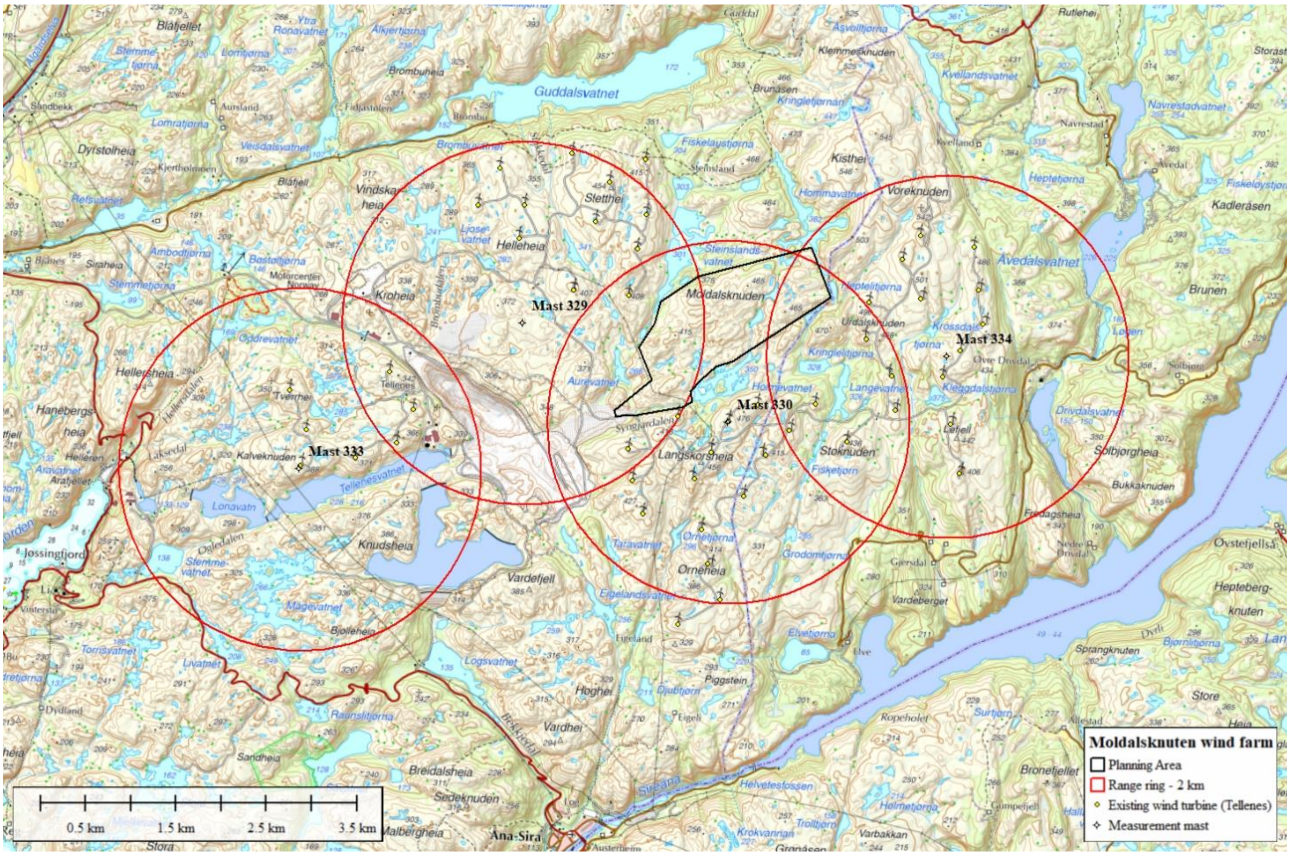

Figure 1 – Moldalsknuten planning area with existing turbines at Tellenes wind farm and measurement masts with 2km distance circles.

The expected energy production is calculated for two different layout alternatives consisting of 8- and 7 wind turbines, respectively. Both layouts are evaluated using the Siemens SWT-DD-130-4.3MW turbine with 115m hub height.

2 Wind data

2.1 Measurement data

MEASNET and TR6 standards state that the duration of a measurement campaign should be at least one year, and the representativeness of measurements is not expected to exceed 2km from the measurement positions in complex terrain. According to the guidelines, wind conditions should also be measured at a height of at least 2/3 of the expected hub height to provide sufficient vertical coverage.

As seen in the above figure, the Moldalsknuten planning area is within a 2km distance from the measurement locations. With measurement periods ranging from 1.8 to 9.5 years from the four local masts, both the temporal and horizontal data coverage is considered sufficient. With the highest measurement height being well below the recommended 2/3 of the planned hub height, relatively high uncertainty in the vertical extrapolation is expected. Validation of the results against the using 6 years of aggregated production data from the Tellenes wind farm was used to reduce this uncertainty (see Section 4.2 for additional information).

The four measurement masts included in the analysis were all 50 m masts equipped primarily with NRG equipment and two Riso sensors at the top height. A summary of the masts and respective instrumentation is included in Table 1.

Table 1 – Tellenes measurement summary (mast 329 – 334)

Equipment	Mast 329		Mast 330		Mast 333		Mast 334	
Coordinates (Zone 32, UTM WGS 84)	E349524 N6469865		E351782 N6468771		E347056 N6468254		E354204 N6469493	
Data Start Date	22.11.2005		15.12.2005		31.08.2006		27.09.2006	
Last Data Available for report	02.05.2015		02.07.2008		03.07.2008		01.07.2008	
Mast/Lidar type	50 m Tubular		50 m Tubular		50 m Tubular		50 m Tubular	
Anemometer	50.0 m	Riso P2546A	49.1 m	Riso P2546A	50.0 m	Riso P2546A	49.1 m	Riso P2546A
	50.0 m	Riso P2546A	49.1 m	Riso P2546A	50.0 m	Riso P2546A	49.1 m	Riso P2546A
	48.7 m	NRG #40	48.0 m	NRG #40	48.4 m	NRG #40	47.6 m	NRG #40
	30.0 m	NRG #40	30.0 m	NRG #40	30.0 m	NRG #40	30.0 m	NRG #40
	10.0 m	NRG #40	9.9 m	NRG #40	10.0 m	NRG #40	10.0 m	NRG #40
Wind Vane	43.1 m	NRG #200P	43.7 m	NRG #200P	44.5 m	NRG #200P	43.6 m	NRG #200P
	9.3 m	NRG #200P	9.2 m	NRG #200P	9.3 m	NRG #200P	9.3 m	NRG #200P
Temperature	2.0 m	NRG 110S	2.0 m	NRG 110S	2.0 m	NRG 110S	2.0 m	NRG 110S
Pressure	-	-	-	-	-	-		-
Relative Humidity	-	-	-	-	-	-		-

The mast data filtering and data handling previously performed and presented in the previous project assessment report [1] was used without change.

2.2 Vertical extrapolation

As the highest measurement heights at the masts are well below the potential hub height of 115 m, the wind data had to be extrapolated vertically. This is normally performed at masts with reliable data at two or more heights using the measured wind shear. The wind shear for each 10-minute data point is then determined using the best fit of the available heights and the shear factor is then used to estimate the wind speed at the desired height. While the lowest measurement height at 10 m was considered too low (too influenced by the terrain conditions), the wind measurements at the two upper NRG sensors at all four masts were used to calculate the shear factor used to extrapolate the Riso Mix-time series vertically. Due to high uncertainty related to the low measurement heights, the wind data was only extrapolated up to 92 m (hub height for the Tellenes wind turbines). Further extrapolation was performed using the flow model.

2.3 Long term correction

While the filtered wind data were used without changes, the long-term correction of the measured data was updated using a reference dataset of higher quality than used for the previous project assessment [1], covering more recent time periods as well.

The reference data used for the long-term correction is the EMD-WRF Europe+ (ERA5), which is a high-resolution mesoscale dataset modelled by EMD. The mesoscale model is run at a spatial resolution of 3x3 km with hourly temporal resolution. ERA5 data from ECMWF (http://www.ecmwf.int) is used as the global boundary data set. The 20-year period from 01.01.2004 to 01.01.2024 was used as reference in the long-term correction. No significant trends were found in this dataset for the period of interest.

The sectoral regression MCP method was used for long-term correction of the wind data measured at the mast position. In this method, the concurrent data between the wind measurements and reference data were analysed using 24 wind direction sectors and a linear regression analysis. The relationship found for each sector is applied to the reference data for the entire reference data period.

Statistics from long-term correction of data extrapolated to 92 and 115 m height are presented in Table 2.

Table 2 - Results of long-term correction of vertical extrapolated wind data

Mast ID	Height [m]	Mean wind speed (measured) [m/s]	LTC wind speed [m/s]	Correlation - wind speed[3]	Correlation - wind speed[4]	Std. Error - wind speed
329	92[1]	7.69	7.67	0.90	0.83	0.24
	115[2]	8.09	8.07	0.90	0.83	0.27
330	92[1]	8.46	8.72	0.92	0.85	-0.32
	115[2]	8.79	9.07	0.91	0.85	-0.32
333	92[1]	8.82	8.90	0.91	0.85	-0.28
	115[2]	9.09	9.17	0.91	0.85	-0.28
334	92[1]	8.31	8.12	0.90	0.83	-0.45
	115[2]	8.70	8.49	0.90	0.83	-0.45

1 Extrapolated using measured shear
2 Extrapolated using combination of measured shear and modeled shear
3 Correlation between reference data and measured data
4 Correlation between long term corrected data and measured data

As seen in the above table, there is a high correlation between the long term corrected data and the extrapolated measurement data, giving confidence in the long term corrected results.

3 Flow model

The WindSim flow model described in the wind resource and production assessment for Moldalsknuten from 2016 was used for this updated assessment without change [1].

4 Production analysis

4.1 Layouts

The two layouts used for the production analysis for Moldalsknuten were provided by the Client and are presented in Figure 2 and Figure 3, together with the 50 existing Tellenes turbines (Siemens S113-3.2MW with 92.5 m hub height).

Both layouts at Moldalsknuten were evaluated using Siemens SWT130-4.3MW-turbines with 115 m hub height.

The Tellenes wind farm is composed of 19 turbines located in Lund municipality with the remaining 31 located in Sokndal municipality.

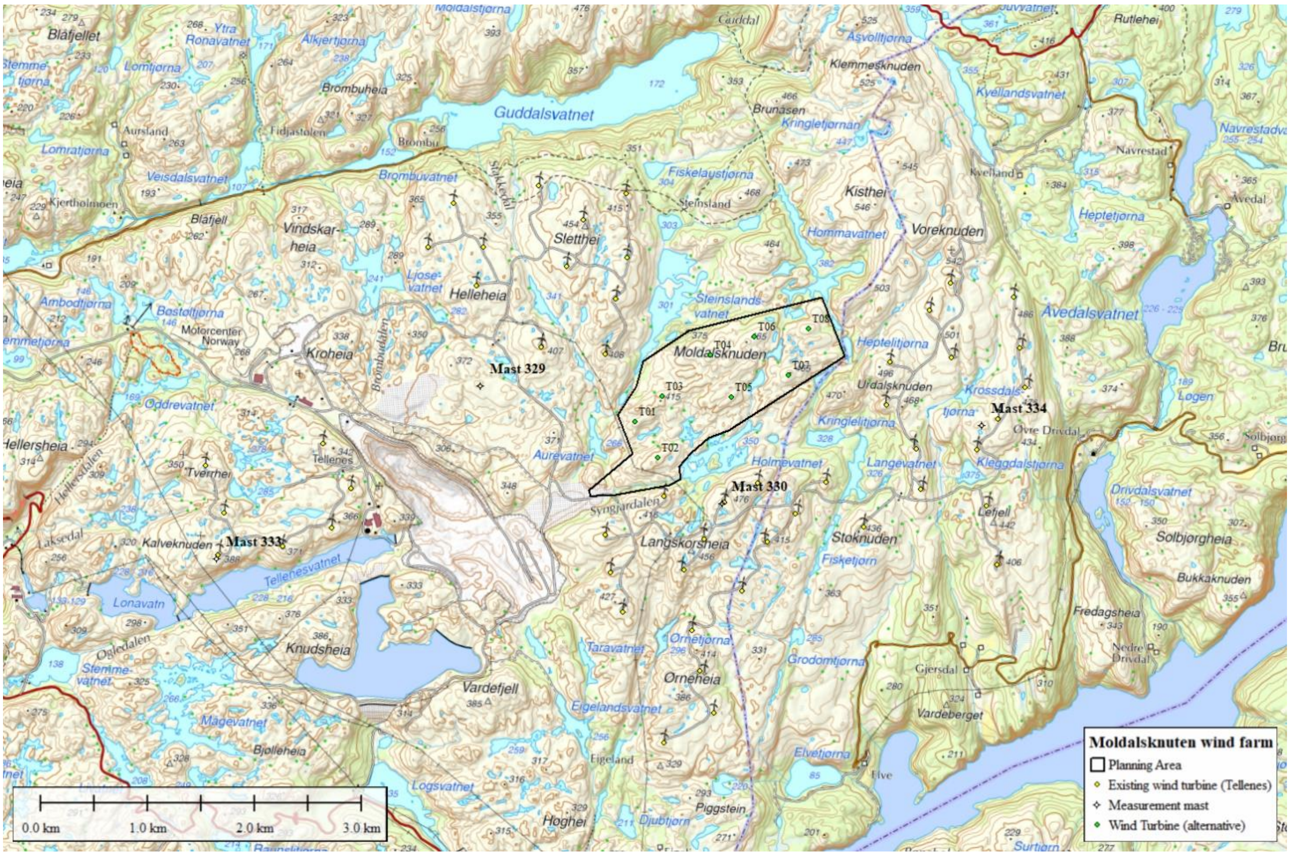

Figure 2 – Wind turbine layout L01a (red dots), Tellenes existing wind turbines (yellow dots)

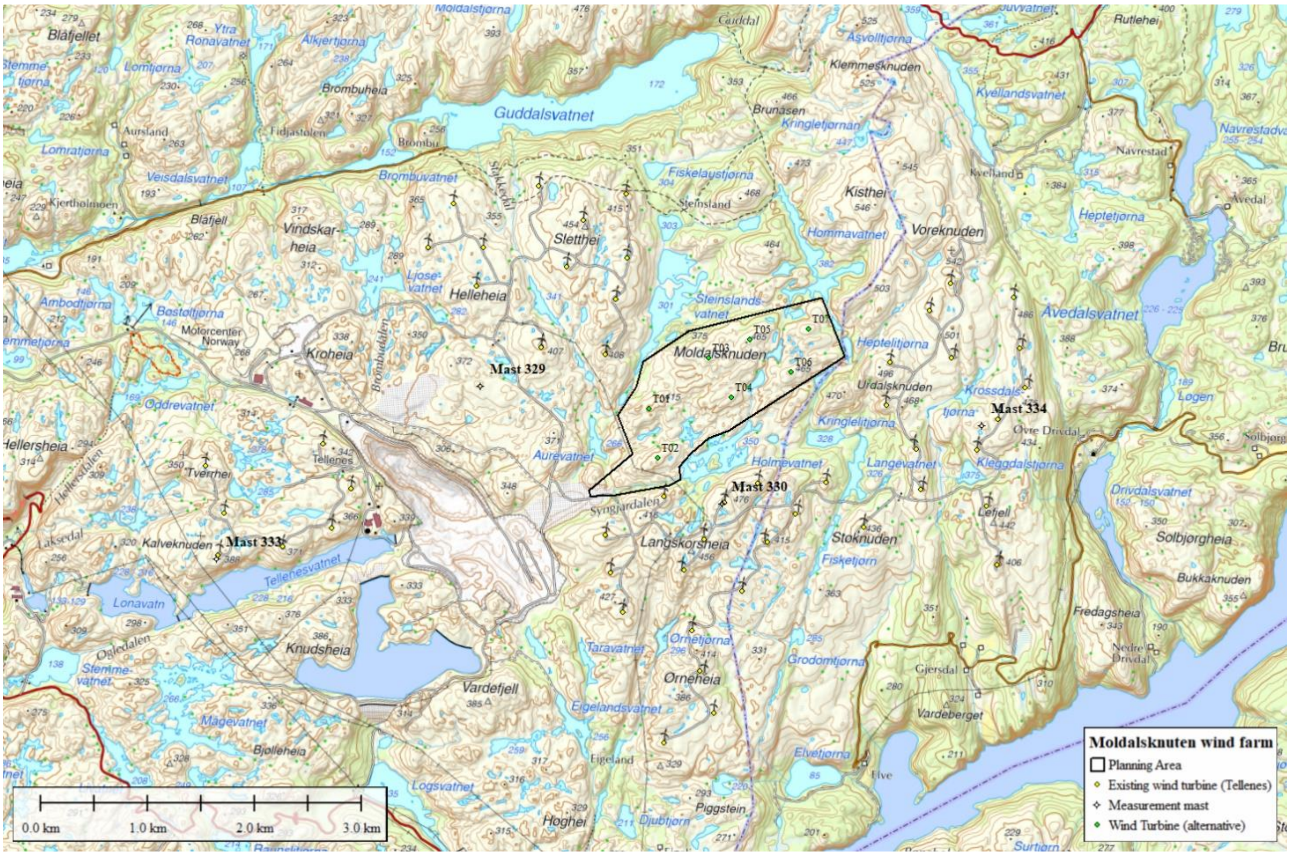

Figure 3 – Wind turbine layout L01b (red dots), Tellenes existing wind turbines (yellow dots)

4.2 Production estimates and validation

The annual energy production was estimated using the standard industry software WindPRO version 4.0.552 and is based on the long term corrected time series, a FlowRes (result) file from WindSim and turbine information provided by the turbine manufacturer. The calculations include an estimate of the gross energy production (no losses), wake losses, estimated additional losses and an expected P50 energy production during the project lifetime. The estimated P50 energy production, after validation from the actual production in the process described below, is provided for both wind farms in Table 3. Additional parameters are presented for Moldalsknuten wind farm in Table 4.

4.2.1 Validation

To reduce uncertainty in the production calculations, 6 years of actual production data from the Tellenes wind farm were used to validate the results. Using publicly available hourly production data from the Tellenes grid metering points for the years 2018-2023 [3], the actual net P50 production data was aggregated to monthly values and compared to a monthly production index for the respective period. These production indexes were calculated in WindPRO based on 20 years of reference data from the EmdWrf-Europe+ (ERA5) dataset and converted to production using the respective Tellenes turbine power curve. The expected long term net production level for Tellenes was found by linear regression between the monthly production values and the corresponding production index values (see Figure 4 below).

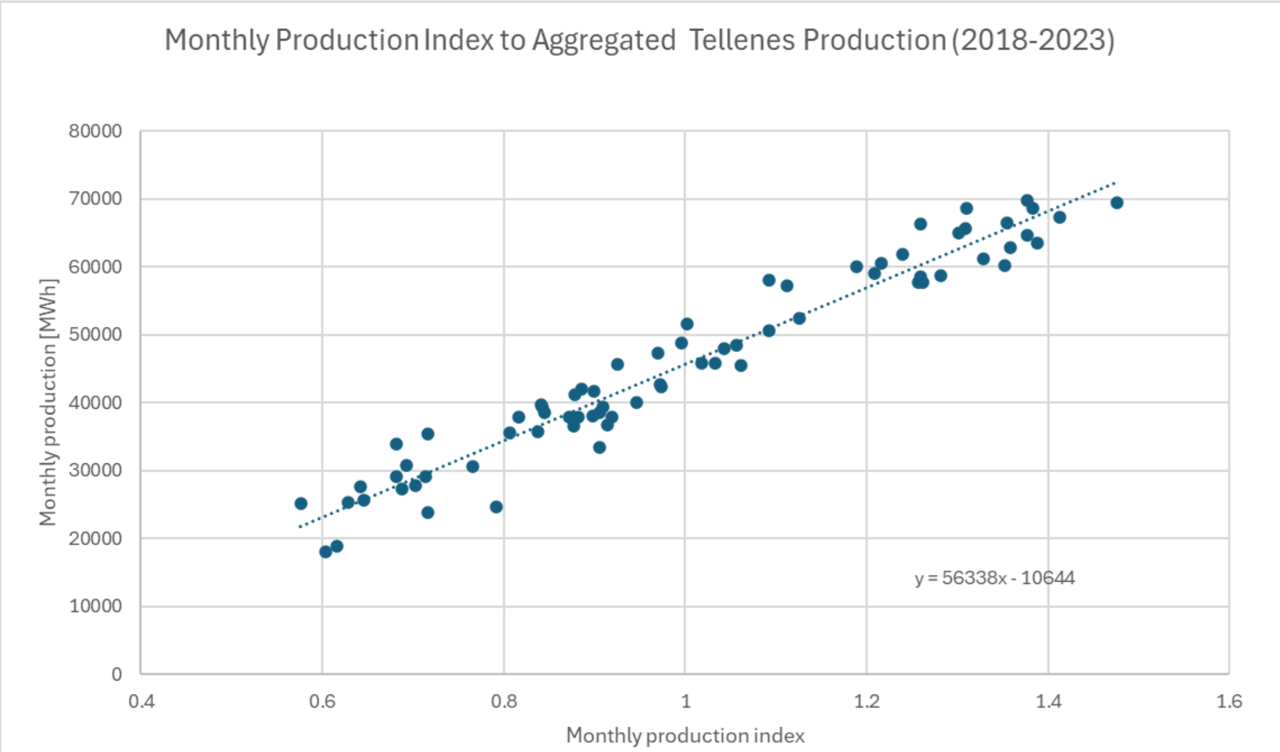

Figure 4 – Regression plot – Monthly production index values versus Tellenes Net Monthly production

As seen in Figure 4, there is a good fit between the monthly production values and the corresponding production indexes, giving confidence the regression fit equation represents a good relationship between the monthly production index and actual production. As a production index value of 1 indicates the average monthly production over the 20-year long term reference period, inputting 1 into this regression fit equation and multiplying by 12 gives the expected long term net production level, assuming all losses experienced between 2018 and 2023 were representative of the long-term period. Historical loss information for the project was not available to verify this assumption. The resulting production level based on historical production data was calculated at 548 GWh/yr.

As wake and other losses for a project are calculated from gross energy production levels, converting the resulting net production value to gross production was necessary for the evaluation. This was performed by applying the percent wake and other losses calculated using the wind measurements and flow model to the net production. The resulting gross production derived from the actual production deviated by only 0.3 % from the gross value derived from the wind measurements and flow model, indicating the estimated production and production loss estimates are representative of the site.

4.2.2 Production estimates

By using the estimated gross production and considering all derived loss values, including an expected future turbine degradation, the net P50 energy production for Tellenes wind farm was estimated at 544 GWh/yr.

An overview of the estimated P50 energy production for both Tellenes and Moldalsknuten wind farm, for each of the two layout alternatives at Moldalsknuten, are presented in Table 3 below. The results are also separated into expected levels for Sokndal and Lund municipalities.

Table 3 – Estimated P50 energy production for Tellenes and Moldalsknuten

Estimated P50 energy production per year [GWh/yr]									
Wind Farm	Without Moldalsknuten wind farm			With Moldalsknuten wind farm					
				8 turbines (L01a)			7 turbines (L01b)		
	Sokndal	Lund	Total	Sokndal	Lund	Total	Sokndal	Lund	Total
Tellenes	342.2	201.8	544.0	336.1	196.8	532.9	337.1	197.2	534.2
Moldalsknuten	-	-	-	103.9	-	103.9	94.0	-	94.0

Further details on the estimated energy production for the two layouts at Moldalsknuten are presented Table 4, along with the expected external wake losses caused by Tellenes wind farm. The estimated reductions in net energy production (P50) at Tellenes wind farm, caused by each of the two layouts, are also included in the table.

Table 4 – Estimated energy production with expected losses for Moldalsknuten wind farm

Parameter	Unit	L01a	L01b
Turbine Type	-	SWT-DD-130	
Capacity	MW	4.3	
Hub height	m	115	
Turbine class (IEC)	-	S/IB	
Total number of turbines	#	8	7
Park capacity	MW	34.4	30.1
GROSS energy production	GWh/yr	149.7	132.0
Net energy production (only wake loss included)	GWh/yr	124.1	110.9
Net energy production (P50)	GWh/yr	103.9	94.0
Wake losses (Internal)	%	7.0	5.8
Wake losses (External) (caused by Tellenes wind farm)	%	10.1	10.2
Other losses (incl. bias)	%	16.2	15.2
Full load hours	h/yr	3021	3123
Mean wind speed at turbines	m/s	8.6	8.6
Reduction in net energy production (P50) at Tellenes wind farm	%	2.0	1.8
	GWh/yr	11.1	9.8

4.3 Production losses

4.3.1 Wake losses

The wake losses are calculated in WindPRO using the same methodology as used for the previous project assessment report [1].

4.3.2 Load curtailment losses

The primary contributor to the other losses presented in Table 4 is related to load curtailment, implemented by Siemens through an Adaptive Control Strategy (ACS) that continuously assesses loading and reduces thrust when climatic conditions exceed design limitations. The ACS is dynamic and not implemented as a fixed curtailment strategy. As it reduces the turbine thrust when active, it consequently also leads to reduced wake losses.

There is not enough public information about the system functionality to calculate these losses independently, so a preliminary Siemens assessment provided by the Client was used. This assessment included the ACS losses, per turbine, defined as a percentage of gross production. Although there were some deviations in the turbine positions (some up to 63 m) used for the Siemens ACS curtailment loss calculations, the losses were assumed representative of the current layouts. Some minor changes to the loss values may occur when updated with the current turbine positions.

The ACS losses used in the assessment for both layout alternatives are presented in Table 5 below.

Table 5 – Overview of Siemens ACS load curtailment losses

L01a		L01b	
Turbine ID	ACS Curtailment losses (%)	Turbine ID	ACS Curtailment losses (%)
	[%]		[%]
T01	4.5	T01	4.5
T02	9.0	T03B	8.7
T03	9.1	T04	4.4
T04	6.5	T05	8.7
T05	8.8	T06	4.4
T06	6.8	T07	1.8
T07	2.4	T08	3.2
T08	3.2		
Average	**6.3**	**Average**	**5.1**

Note that the calculated wake losses are considered conservative when accounting for the ACS loss in this manner, as the wake losses in reality will be lower in periods where the ACS is active.

4.3.3 Other losses

All other losses are calculated/assumed as described in the previous project report. See [1] for further details.

References

[1] MEV WS 2016-004 – Moldalsknuten Wind Resource and Production Assessment, Meventus, 25.08.2016

[2] MEV WS 2022-001 – Vind og produksjonsindekser for vindkraft i Norge, NVE – 2021, Meventus, 08.02.2022

[3] Data for utbygde vindkraftverk i Norge, NVE, 13.06.2024. https://www.nve.no/energi/energisystem/vindkraft-paa-land/data-for-utbygde-vindkraftverk-i-norge/