Tall towers for large wind turbines

Report from Vindforsk project V-342 Höga torn för vindkraftverk

Elforsk rapport 10:48

Staffan Engström, Tomas Lyrner, Manouchehr Hassanzadeh,
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Preface

The interest of wind power in forested areas in Sweden has been quite high recently. In such areas the economy of a project relies heavily on being able to have e high tower to reach good winds and low wind shear.

The project "Tall towers for wind turbines" has been carried out to look at the economy of different tower concepts.

The work was carried out by Staffan Engström, Ägir Konsult, Tomas Lyrner, WEC and Manouchehr Hassanzadeh, Thomas Stalin and John Johansson at Vattenfall as a project within the Swedish wind energy research programme "Vindforsk – III". The report is the final report for project V-342.

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Comments on the work and the final report have been given by a reference group with the following members: Milan Vejlkovic, Staffan Nicklasson, o2, Martin Norlund, E.on, Erik Åslund, Fortum and Henrik Berglund, Statkraft

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Summary

The general rule of thumb has been to furnish a wind turbine with a tower as tall as the turbine diameter, with deviations downwards for high wind speed sites. In this report the statement is questioned, with special emphasis for wind turbines sited in forests.

During the last few years, siting of large wind turbines in forested areas has become quite common in Sweden and also in e.g. Germany. The application provides large areas with a reasonable to excellent wind resource and little conflict with other interests, e.g. habitation. The trees create a large wind shear, which naturally favours high hub heights. The trees also often increase the turbulence level, which decreases with increasing height, and thus forms another incentive for using tall towers.

The aim of this project was to propose and calculate candidate types of tall towers for on-shore wind turbines in the 3 - 5 MW range, with special reference to siting in forests with a representative wind shear.

During the project this scope has been more precisely defined to study 3 and 5 MW wind turbines with hub heights of 80 - 175 meters featuring the following tower solutions:

1. Steel shell tower designed in a conventional way with flanges and both longitudinal and transverse welds.
2. Steel shell tower with bolted friction joints only.
3. Concrete tower with pretensioned steel tendons.
4. Hybrid tower with a lower concrete part and an upper part built as a conventional steel shell.
5. Lattice tower.
6. Wooden tower.

One important objective of the project was to calculate all towers under the same conditions, enabling comparisons even if the conditions themselves always may be questioned to some extent. During the execution of the project the design of a total of 42 towers was outlined and calculated.

Today the welded steel shell tower dominates the wind turbine market. Larger turbines and higher hub heights result in larger optimal tower base diameters. For the road transportation there are limitations due to bridges and other obstacles. In Sweden the limit for transports with special permits in general maximizes the diameter to 4,5 metres. In other areas the restrictions may be more severe. To some extent it is still technically possible to build towers with a less than optimal diameter, but due to the high mass and the large wall thickness they tend to be uneconomical in comparison with other alternatives above a hub height of roughly 100 metres. In this report welded steel shell towers were outlined for 3 MW turbines up to a hub height of 150 metres whereas the limit for the 5 MW towers was 100 metres.

When diameter restrictions tend to make welded towers uneconomical, the next logical choice is steel shell towers with bolted friction joints both longitudinally and laterally. Such a tower is transported as the separate cut, bent, drilled and painted steel plates, which are assembled at the turbine site.

This technology was in use already during the 1980s for the much smaller turbines of that time. Today it is just starting to reappear.

Also pretensioned concrete towers have a long history in wind power, starting with in-situ built slip formed towers. Today most concrete towers are assembled from prefabricated elements, cast in sizes allowing road transportation.

The advantages of the concrete towers are concentrated to the lower parts, which are capable of absorbing large moments in an economical way. Therefore hybrid towers are appearing on the market, with a concrete part for the lower section and a conventional steel shell tower for the upper. This solution also provides the designer with some freedom regarding both the design of the concrete tower and the placement of the eigenfrequencies of the tower. From this study one can draw a quite firm conclusion that hybrid towers generally are more economical than pure concrete ones.

Due to the very large base width, lattice towers reveal the lowest weights and investments of all towers. The so far tallest wind turbines have been furnished with lattice towers. The advantages are counteracted by disadvantages that may be equally strong. The number of bolts is very high and they need periodic checking. The dynamic properties are hard to control. During icing conditions large accumulation of ice in extreme cases may endanger the turbine. An acceptable level of safety for the maintenance personnel may be hard to maintain. And finally the visual qualities are controversial.

Wood has been used as a construction material for wind turbine blades for decades, but only recently considered for wind turbine towers. This may seem strange, since towers should be a less demanding application than blades. Wood is also in general known to be an economical construction material resistant to fatigue and buckling. The so far only large wind turbine tower of wood is designed by a German company for a 1,5 MW wind turbine. In this report the wooden towers were studied less extensively than the others, due to the less developed and known technology especially regarding joints.

Today mobile cranes are the dominating way of lifting tower segments and turbines. With the cranes available today and current weights there is a limit of 125 - 150 metres in hub height for this technology. Still higher hub heights may be served with lifting towers, which however today are quite expensive and in this report the immediate reason why hub heights above 150 metres were uneconomical. Thus there is a need for more economical ways of lifting wind turbines to the highest hub heights.

From the study one can draw a general conclusion that it is economical to build taller towers than the hitherto conventional one turbine diameter. This tendency is more pronounced in a forest than in the open farmland, which is due to the higher wind shear above a forest. However, larger turbines, in terms of turbine diameter and power level, are not more economical, at least not with the turbines specified for this study.

Looking at e.g. a hub height of 125 metres, it is possible to save up to 30 % of the tower cost by selecting another technology than the conventional welded steel shell tower. Besides lattice towers also wooden towers came out as being surprisingly economical. In general one can conclude that there are today several interesting alternatives worthy of further development – steel shell towers with friction joints, concrete towers, hybrid concrete/steel towers, wooden towers and lattice towers.

Sammanfattning på svenska

Enligt en gängse tumregel är det ekonomiskt att utrusta vindkraftverk med ett torn som är lika högt som storleken av turbindiametern, med en justering nedåt för vindrika platser. I den här rapporten ifrågasätts detta påstående, i synnerhet för vindkraftverk som placeras i skog.

Lokalisering av stora vindkraftverk i skogsmark har på senare år blivit vanligt i Sverige och även i exempelvis Tyskland. Tillämpningen medger stora ytor med rimliga till utmärkta vindförhållanden och små konflikter med andra intressen, t. ex. bebyggelse. Träden orsakar en kraftig vindgradient, vilket gynnar höga torn. Träden orsakar ofta även en ökad turbulens, som emellertid avtar med ökande höjd och därmed utgör ett ytterligare argument för höga torn.

Målet för projektet var att föreslå och beräkna lämpliga typer av höga torn avsedda för vindkraftverk på land i storleksområdet 3 - 5 MW, med särskild tonvikt på placering i skog med en representativ vindgradient.

Under genomförandet av projektet preciserades omfattningen ytterligare till att studera 3 och 5 MW vindkraftverk med navhöjd 80 - 175 meter och följande torntyper:

1. Stålrörstorn utförda konventionellt med flänsar och svetsar både i längd- och tvärriktningarna.
2. Stålrörstorn enbart sammansatta med friktionsbaserade skruvförband.
3. Betongtorn förspända med dragstag av stål.
4. Hybridtorn med en undre betongdel och en övre del utförd som ett konventionellt stålrörstorn.
5. Fackverkstorn.
6. Trätorn.

Ett viktigt syfte med projektet var att beräkna samtliga torn under samma förutsättning, i avsikt att medge inbördes jämförelser, även om förutsättningarna till viss del alltid kan ifrågasättas. Under projektet var det totalt 42 torn som översiktligt konstruerades och beräknades.

Idag domineras vindkraftsmarknaden av det svetsade stålrörstornet. Större turbiner och högre tornhöjder resulterar i att den optimala diametern vid tornfoten ökar. Vägtransporten innebär emellertid begränsningar på grund av broar och andra hinder. I Sverige medges i allmänhet dispenser för transporter med specialtillstånd till som mest 4,5 meters torndiameter. I andra områden kan restriktionerna vara ännu strängare. I viss utsträckning är det möjligt att bygga torn med mindre diameter än den optimala, men den höga vikten och stora väggtjockleken tenderar att göra dessa oekonomiska i jämförelse med andra alternativ över grovt sett 100 meters höjd. I rapporten skissas utförandet av svetsade stålrörstorn för upp till 150 meters navhöjd för 3 MW vindkraftverk, medan gränsen för 5 MW verk blev 100 meter.

När restriktioner för diametern börjar göra svetsade torn oekonomiska är den naturliga slutsatsen att utföra stålrörstorn med friktionsförbindningar med skruvförband i såväl i längd- som tvärriktningarna. Ett sådant torn transporteras i form av de enskilda tillskurna, bockade, borrade och målade

stålplåtarna, vilka monteras tillsammans först på montageplatsen. Tekniken tillämpades redan på 1980-talet för den tidens betydligt mindre vindkraftverk. Idag har den precis börjat användas igen.

Även förspända betongtorn har en lång historia inom vindkraften, initialt med glidformsgjutna betongtorn utförda på plats. Idag tillverkas de flesta betongtorn av prefabricerade element, som gjuts i storlekar som tillåter vägtransport.

Fördelarna med betongtorn är störst i de nedre delarna av tornet, där betongen kan uppta de stora momenten på ett ekonomiskt sätt. Därför har hybridtorn börjat uppträda på marknaden, med betong i nederdelen och ett konventionellt stålrörstorn i överdelen. Denna lösning ger även konstruktören en viss frihet beträffande både betongtornets konstruktion och placeringen av tornets egenfrekvenser. Från studien kan man dra en tämligen säker slutsats ett hybridtorn generellt är mer ekonomiska än rena betongtorn.

Till följd av den mycket stora tornbasen får fackverkstorn den lägsta vikten och kostnaden av alla torn. De hittills högsta vindkraftverken har försetts med fackverkstorn. Fördelarna motverkas av nackdelar som kan vara lika stora. Antalet skruvförband i ett fackverkstorn är mycket stort och kräver periodisk tillsyn. De dynamiska egenskaperna är svåra att kontrollera. Vid isbildning kan ispåslaget i extrema fall bli så stort att det hotar vindkraftverkets existens. Egenskaperna med hänsyn till arbetarskydd kan vara tveksamma. Slutligen är de visuella egenskaperna kontroversiella.

Trä har använts som ett konstruktionsmaterial i vindturbinblad sedan tiotals år, men först på senare tid i torn för vindkraftverk. Detta kan verka underligt, eftersom torn bör vara en mindre krävande tillämpning än blad. Och trä är generellt känt som ett ekonomiskt konstruktionsmaterial som är motståndskraftigt mot utmattning och buckling. Det hittills enda stora vindturbintornet av trä har tillverkats av ett tyskt företag för ett 1,5 MW vindkraftverk. I denna rapport behandlades trätorn på ett mindre inträngande sätt än för övriga material, till följd av den mindre utvecklade och kända tekniken, särskilt vad gäller skarvar.

Idag är mobilkranar det dominerande sättet att lyfta torndelar och turbiner. Med de kranar som är tillgängliga idag och aktuella vikter klarar denna teknik idag lyfthöjder upp till 125 - 150 meter. Ännu högre navhöjder kan åstadkommas med hjälp av lyfttorn, vilket dock idag är en dyrbar teknik som är den direkta anledningen till att navhöjder över 150 meter i denna rapport bedömdes som oekonomiska. Det finns således ett behov av mer ekonomiska metoder för att lyfta vindturbiner till de högsta navhöjderna.

From the study one can draw a general conclusion that it is economical to build taller towers than the hitherto conventional one turbine diameter. This tendency is more pronounced in a forest than in the open farmland, which is due to the higher wind shear above a forest. However, larger turbines, in terms of turbine diameter and power level, are not more economical, at least not with the turbines specified for this study.

En generell slutsats från studien är att det är ekonomiskt att bygga högre torn än den sedvanliga en turbindiameter. Denna tendens är starkare i skog än i ett öppet jordbrukslandskap, beroende på den starkare vindgradienten över skogen. Emellertid kan man inte visa att större vindkraftverk, mätt som turbindiameter och effekt, skulle vara mer ekonomiska, i alla fall inte med de vindkraftverk som specificerats för denna studie.

Om man exempelvis betraktar vindkraftverk med 125 meters navhöjd, är det möjligt att spara upp till 30 % av tornkostnaden genom att välja en annan teknologi än det konventionella svetsade stålrörstornet. Förutom fackverkstorn föreföll även trätorn vara förvånansvärt ekonomiska. Generellt kan man dra slutsatsen att det idag finns ett flertal alternativ som är värda fortsatt utveckling - stålrörstorn sammansatta med friktionsförband, betongtorn, hybridtorn av betong och stål, trätorn och fackverkstorn.

Contents

1 Background and scope of work

1.1 Background

The general rule of thumb has been to furnish a wind turbine with a tower as tall as the turbine diameter, with deviations downwards for high wind speed sites. During the last few years, siting of large wind turbines in forested areas has become quite common in Sweden and also in e.g. Germany.[1] The application provides large areas with a reasonable to excellent wind resource and little conflict with other interests, e.g. habitation. The trees create a large wind shear, which naturally favours high hub heights. The trees also often increase the turbulence level, which decreases with increasing height, and thus forms another incentive for using tall towers.

1.2 Tower types to be studied

The Vindforsk project V-342 "Höga torn för vindkraftverk" was started in December 2009. The aim was to propose and calculate candidate types of tall towers for wind turbines in the 3 - 5 MW range, with special reference to siting in forests with a representative turbulence level and wind shear.

During the project this scope has been more precisely defined to study 3 and 5 MW wind turbines with hub heights of 80 - 175 meters featuring the following tower solutions:

1. Steel shell tower designed in a conventional way with flanges and both longitudinal and transverse welds. Due to transportation reasons the largest permitted diameter is 4,5 meters.
2. Steel shell tower with bolted friction joints only.
3. Concrete tower with pretensioned steel tendons.
4. Hybrid tower with a lower concrete part and an upper part built as a conventional steel shell (type 1 above).
5. Lattice tower.
6. Wooden tower. Simplified study with no consideration to connections to foundation and nacelle, nor to necessary joints.

1.3 Execution of work

The main calculation work has been carried out by Tomas Lyrner, WEC, whereas Staffan Engström, Ägir konsult, has been responsible for the planning and the compilation of the report. The team of Manouchehr Hassanzadeh, Thomas Stalin and John Johansson from Vattenfall have

[1] See e.g. Regarding wind and wind power in forests. Statens Energimyndighet. ER 2008:21 (in Swedish).

provided background information, mainly by way of a report[2] which covers the extensive work on the application of tall towers for wind turbines effected by Vattenfall and which kindly has been made available for the purpose of this study.

[2] Manouchehr Hassanzadeh, Thomas Stalin and John Johansson. High Towers for wind power onshore. Information dissemination. Vattenfall Research and Development AB. 2008-12-05.

2 Turbine types and way of calculation

2.1 5 MW turbine

As the reference turbine for the 5 MW size, the NREL 5 MW Baseline 126 meter diameter turbine was selected[3]. An advantage of this choice is that the design is fairly well documented. Since it has been used in simulations performed by e.g. Teknikgruppen, missing data are rather easy to retrieve. The main data are summarized in Table 1.

The NREL turbine has never been built in reality, although it to a large extent resembles the REpower 5 MW turbine, which has been built both onshore and offshore. Alternatively one might have taken a turbine actually built, e.g. the one mentioned from REpower. The drawback is that some data may not be available for that turbine or may have been received with restrictions for further use. Main data as in Table 1 and power curve in Table 2.

Table 1. Main data for NREL 5 MW wind turbine (without tower)

Power	5 MW
IEC Class	IB
Rotor orientation	Upwind
Number of blades	3
Control	Variable speed, collective pitch
Turbine diameter	126 m
Rated rotor speed	11,8 rpm (0,20 Hz)
Blade passage frequency (3 p)	0,59 Hz
Rated tip speed	78 m/s
Blade weight (each)	18,8 ton
Hub weight	53,6 ton
Rotor weight	110 ton
Nacelle weight	240 ton
Tower top weight	350 ton

[3] NREL Offshore Baseline 5 MW. Jason Jonkman, NREL/NWTC, August 11, 2005. National Renewable Energy Laboratory, Denver, Colorado.

Table 2. Power curve 5 MW

Wind speed, m/s	*Power, kW*
0-3	0
4	144
5	368
6	720
7	1159
8	1773
9	2484
10	3169
11	3849
12	4512
13	4850
14-25	5000

2.2 3 MW turbine

The 3 MW wind turbine was created by scaling data for the previously described NREL 5 MW Baseline turbine. Results are depicted in Table 3 and the estimated power curve in Table 4.

Reasons for using such a "faked" turbine is the availability of the baseline design and that it will make the study consistent. The general results look like a mainstream 3 MW turbine of today.

Table 3. Main data for 3 MW turbine, derived from NREL 5 MW turbine

Power	3 MW
IEC Class	IB
Rotor orientation	Upwind
Number of blades	3
Control	Variable speed, collective pitch
Turbine diameter	100 m
Rated rotor speed	14,0 rpm (0,23 Hz)
Blade passage frequency (3 p)	0,70 Hz
Rated tip speed	73 m/s
Blade weight (each)	10,5 ton
Hub weight	25 ton
Rotor weight	56,5 ton
Nacelle weight	120 ton
Tower top weight	176,5 ton

Table 4. Power curve 3 MW

Wind speed, m/s	*Power, kW*
0-3	0
4	91
5	232
6	454
7	730
8	1117
9	1565
10	1996
11	2424
12	2822
13	2974
14-25	3000

2.3 Wind conditions and hub heights

The wind data selected for the study is representative of large areas of forested land in south Sweden, as revealed in the extensive measurement program conducted by Vattenfall.[4] At a height of 100 meters the mean wind speed is 6,2 m/s, which is quite low compared with e.g. IEC wind class III (7,5 m/s). Due to the high wind shear (exponent 0,33), the wind conditions at higher hub heights are substantially better. Sites in reasonably open areas normally have a wind shear of around 0,2. The selected heights were 80, 100, 125, 150 and 175 meters, corresponding to 0,8 – 1,8 turbine diameters for the 3 MW turbine and 0,6 – 1,4 diameters for the 5 MW case. The conventional choice for sites with normal wind shear (0,2) is mostly about one turbine diameter.

Table 5. Wind data and hub heights selected for the study.

Wind shear exponent 0,33, Zero-plane displacement 15 m, Weibull shape factor C 2,5.

Height above ground	*Mean wind speed*	*Vref*	*Tower height as number of turbine diameters*		*Annual production MWh*	
m	*m/s*	*m/s*	*100 m*	*126 m*	*3 MW*	*5 MW*
80	5,67	28,4	0,8	0,6	5 000	7 945
100	6,20	31,0	1,0	0,8	6 328	10 070
125	6,75	33,8	1,3	1,0	7 770	12 392
150	7,22	36,1	1,5	1,2	9 016	14 411
175	7,64	38,2	1,8	1,4	10 100	16 178

[4] Ref. Magnus Andersson, Vattenfall R&D, Personal message, 2010-01-27

The zero-plane displacement used in the table corresponds to the ground level as experienced by the wind, which mostly is taken 2/3 to ¾ of the height of the trees.[5]

Note that the values of the turbulence intensity are not used in the report, since no fatigue calculations were carried out.

2.4 Way of calculation

Initially it was assumed that towers would be dimensioned by the "storm parking load case", i.e. the turbine at standstill during the 50-year wind case according to the IEC 61400-1 Ed. 3[6]. However, when starting calculations it appeared that with mean wind speeds as low as stated for this report, this was not the case. Instead, it was found that the worst case is shared rather equally by the following load cases, which appear during normal operation at rated power: extreme wind shear, extreme operating gust and extreme turbulence model. The loads thus calculated have been increased by multiplication with partial coefficients etc as stated in the standard. One set of loads were calculated for each hub height and then used for all types of towers. The simulations were performed with the Vidyn model, developed by Teknikgruppen AB.[7]

Fatigue has not been considered, primarily since this appeared to make the workload beyond what was available for this rather limited study. This may implicate that the steel alternatives, and especially the welded steel towers, have been treated too favourable. However, mostly a fatigue check does not change the initial dimensioning of a steel tower. The concrete and wood towers are not considered to be sensitive to fatigue.

The main results of this report are revealed as the *Specific investment cost*, calculated as the investment of the wind turbine (including foundation, except site costs, roads, grid connection etc) divided by the yearly production. This means that no consideration is given to maintenance cost. Please also note that in the summarizing tables, *Relative wind turbine investment* is related to the 80 m hub height case of that alternative, whereas *Relative energy production investment* relates to the 3 MW, 80 m welded tower case.

Most towers were considered "soft", which means that at full rpm the operation is overcritical in relation to the normal "3p"-criteria, i.e. the frequency of the three disturbances per revolution of the turbine (one for every blade passage) is higher than the first bending frequency of the tower. Some towers were even "softsoft", indicating that operation also exceeded the 1p-level. In one case (125 m welded steel) the tower frequency happened to coincide with the rotational frequency, which means this tower in reality can not be used, since a fault case with one blade in wrong pitch position would cause very large moments due to the resonance. For the purpose of this

[5] H. Bergström. Wind Mapping of Sweden. Summary of results and methods used. Elforsk 09:04

[6] IEC 61400-1 Wind turbines – Part 1: Design requirements, accepted as Swedish standard SS-En61400-1 ed. 3 of 2006-02-27, with Amendment 1 to IEC 61400-1 Ed. 3 Wind Turbines Part 1: Design Requirements, of 2009-01-16.

[7] H. Ganander**.** The use of a code-generating system for the derivation of the equations for wind turbine dynamic. Wind Energy, vol. 6, no. 4.

report it however seemed reasonable to utilize this data. Figures for a non-resonance tower are revealed as well. If this problem appears in a real design situation, the best solution is probably to try to avoid it by increasing or decreasing the tower height. Another way is to increase or decrease the turbine diameter and thereby change the rpm.

In summary, the procedure for dimensioning the towers runs according to the following scheme:

1. Run simulations for the complete wind turbine with the different hub heights in order to determine the maximum axial thrust that affects the tower. The eigenfrequencies of the towers are supposed to not create adverse dynamic effects.
2. Determine adequate partial coefficients etc depending on construction material and type of design.
3. A rough design for each tower type, power level and hub height. Designs modified to avoid conflicting eigenfrequencies when needed
4. Determine amount of construction material and cost for each tower.
5. Determine total cost of each wind turbine using each tower.
6. Determine specific investment cost in relation to electricity production for each wind turbine using each tower.

Note that the two first actions are common for all tower designs of that power level and hub height.

With two power levels, five hub heights and six different types of towers, the programme in all comprised calculation of 60 different towers. Due to different reasons, such as lack of data and the inability to realize some of the designs, the actual number of towers detailed in the report came to be 42.

2.5 Foundation

The weight and cost of the foundation was estimated by assuming that the need of reinforced concrete is proportional to the tipping moment. This further assumes that ground conditions are normal.

2.6 Applicable standards

The work was carried out according to the international standard IEC 61400-1 Wind turbines – Part 1: Design requirements.[8] Else other applicable standards, such as BSK[9], Eurocode etc.

Since the wind turbines except tower are specified for IEC Class I, as mentioned above, they will include a substantial design margin when exposed to the wind conditions of the study, although the turbulence intensity is higher than the anticipated A-level of 0,14 at 15 m/s wind speed. IEC I corresponds to a mean wind speed of 10 m/s at hub height and the highest level in the study is 7,64 m/s.

[8] ibid

[9] Boverkets handbok om stålkonstruktioner, BSK 07. Boverket 2007. www.boverket.se

2.7 Decommissioning

Although not a formal part of the project, some comments regarding the decommissioning of wind turbines with different types of towers may be given as follows.

The problem area has been treated in a report published by Svensk Vindenergi.[10] Metal scrap mostly represents a value, although still this income does not in general cover the cost of dismantling and restoration. After crushing, concrete at best can be given away for free for use as filling material. In total the costs generally are less than 0,1 euro cent per kWh of production during the life of an onshore wind turbine.

[10] Wind Turbines – Survey of activities and costs for dismantling, restoration of site and reclamation. Svensk Vindenergi 2010. (In Swedish.) www.svenskvindenergi.org

3 Installation methods

3.1 Cranes

Most wind turbine assembly operations are performed with mobile cranes, which may be either of crawler type (see Fig. 1) or truck-mounted. Crawler cranes are often the preferred choice, however, they have the drawback of needing quite wide tracks for travel between the turbine sites within a wind park. Of the cranes mentioned below, the LR 1400 needs a 9 m wide track and the LR 1800 needs 12,5 m. In order to avoid excessive costs for roads etc, the crane may be dismantled between use at the successive turbine sites in a wind farm, although such dismantling also involves a cost.

Cranes in general have benefits of a short installation time per turbine and a relatively small crew. Disadvantages are the areas needed for the lifting operation, need for wide roads inside parks, rigging between turbine sites, wind restrictions (maximum 5 – 8 m/s during lifting) and the cost for mobilization and hire, especially of the largest units.

Approximate costs for mobilization and hire are depicted in Table 6. In the calculations of the report, the cost of 300 km of land transportation from Swedish port has been added.

Figure 1. Lifting of the 340 t hub section for Enercon E-126 7,5 MW wind turbine. The Terex Demag CC9800 crawler crane is formally rated 1600 t and in this configuration can lift 360 t.

Table 6. Approximate cost of cranes, including transportation from Belgium to Swedish port[11]			
Type	Weight of unit + equipment	Mobilization cost, 1 000 NOK[12]	Long term hire, per week, 1 000 NOK
Liebherr LR 1400	450 t + 250 t	1 500	125
Demag CC 2800	500 t + 250 t	2 000	150
Liebherr LR 1800	700 t + 300 t	3 500	325
Demag CC8800	800 t + 400 t	4 500	450

3.2 Lifting towers

Lifting towers have traditionally been used in industry for installation of heavy equipment. In the wind industry the technology was used for the early Swedish Maglarp and Näsudden II projects. Recently Scanwind utilized it for the erection of 14 large wind turbines at Hundhammerfjell in Norway. Reasons to select this technology were in this case heavy lifts, uneven terrain and high wind conditions, making it hard to find calm periods for lifting with cranes. With lifting towers it is possible to perform lifts up to 15 – 18 m/s wind speed. The equipment was owned by Scanwind and operated by Sarens Transrig.

The cost to perform the lifting of five Scanwind turbines is today estimated at 4,5 million NOK each, exclusive of the hire of the lifting equipment.[13] The cost to produce an equipment capable of 250 t and 175 m is estimated at 45 million NOK. Provided that the equipment is dimensioned for the case it is used for, and that it is fully used throughout the year, theoretically a 5 % addition may cover the capital cost.

There is ongoing development work aiming at creating less costly alternatives for lifting wind turbines to high heights.[14]

3.3 Equipment for performing lifts

The equipment needed for performing lifts as needed for the cases studied in this report have been compiled in Table 7.

[11] Arne Östraat, Sarens Transrig AS. Feasibility study for installation of large wind turbines. Personal message 2010-05-07.
[12] Exchange rates in this report 1 NOK = 1,25 SEK and 1 euro = 9.60 SEK
[13] ibid
[14] Torbjörn Jonsson, NCC. Personal communication 2010-06-21.

Table 7. Equipment for performing lifts of wind turbines.[15] For maximum hub heights and maximum single lifts as depicted				
Hub height, m	*Max. 70 t*	*Max 120 t*	*Max 140 t*	*Max 240 t*
80	LR 1400/2	LR 1400/2	CC 2600	LR 1750
100	LR 1400/2	CC 2600	LR 1750	LR 1800
125	CC 2800	LR 1750	LR 1800	CC 8800-1
150	LR 1800	LR 1800	CC 8800	Lifting towers
175	LR 1800	Lifting towers	Lifting towers	Lifting towers

Figure 2. Lifting towers in use for assembly of Scanwind 3 MW wind turbine at Hundhammerfjell, Norway. Lifting operation performed by Sarens Transrig AS. Note that the wind turbine tower is used for stabilizing the lifting towers and that a small mobile crane is used for assisting lifts.

[15] ibid

4 Studied towers

4.1 Welded steel shell tower

The welded steel shell tower today dominates the wind turbine market. It consists of cylinders made of steel plate bent to a circular shape and welded longitudinally, see Fig. 3. Transversal welds connect several such cylinders to form a tower section. Each section ends with a steel flange in each end. The sections are bolted to each other. The bottom flange is connected to the foundation and the top one to the nacelle.

A tower is primarily dimensioned against tension and buckling in the extreme load cases. Ideally the margin should be the same for both criteria, since increasing the diameter, with a corresponding reduction of plate thickness, increases the tension strength but reduces the buckling margin. Finally the tower has to be checked against fatigue. According to BSK and Eurocode connecting welds (transversal and longitudinal) and dimension changes (flanges) affects the strength in a negative way. Thus it is the welds and the geometry that primarily determine the fatigue strength rather than the quality of the steel. Therefore wind turbine towers mostly use ordinary qualities of

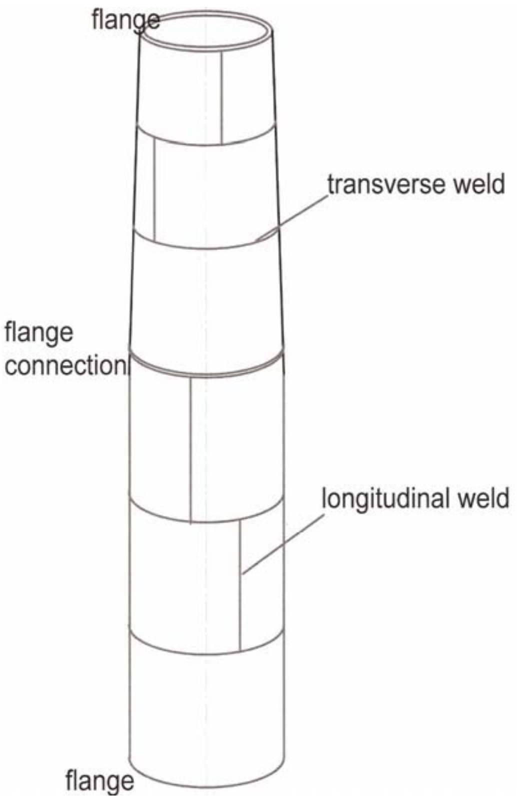

Figure 3. Steel shell tower in two sections.

steel. In this report use of S355J2G3 (earlier known as SS2134, tensile yield limit 355 MPa) is assumed for both the welded and friction joint towers.

In the dimensioning load case, the tower is affected by the thrust from the rotor. This thrust will create a bending moment, which increases with the distance from the turbine shaft, i.e. inversely proportional to the height above the ground. To cope with this increasing bending moment it is favourable to make the tower conical in shape, to the limit of buckling. However, land transportation even with a special permit is not possible for diameters exceeding 4,5 m in Sweden. Other countries and certain roads may create even more severe restrictions, e.g. 3,5 m. To a certain degree these restrictions may be counteracted by an increase of plate thickness, however, the tower will then become less economical. This influence is clearly visible in Table 8.

The calculated cost 2.30 €/kg is a market price (2010) and includes all material and work that goes into the product. For the tower this means steel plate, welding, flanges, screws, nuts, painting etc. In a report from 2008 a similar price was stated as 2,1-2,2 €/kg.[16]

Table 8. Influence of diameter restriction on weight of tower for 3 MW wind turbine.

Hub height	150 m	175 m
Maximum 4,5 m base diameter		
Weight, t	610	-
Plate thickness at base, mm	75	-
Base diameter if not restricted	*5,8*	*6,0*
Weight, t	551	724
Plate thickness at base, mm	43	46

[16] M. Hassanzadeh, T. Stalin and J. Johansson. High towers for wind power onshore – information dissemination. Vattenfall Reasearch and Development AB. 2008-12-05. P. 8.

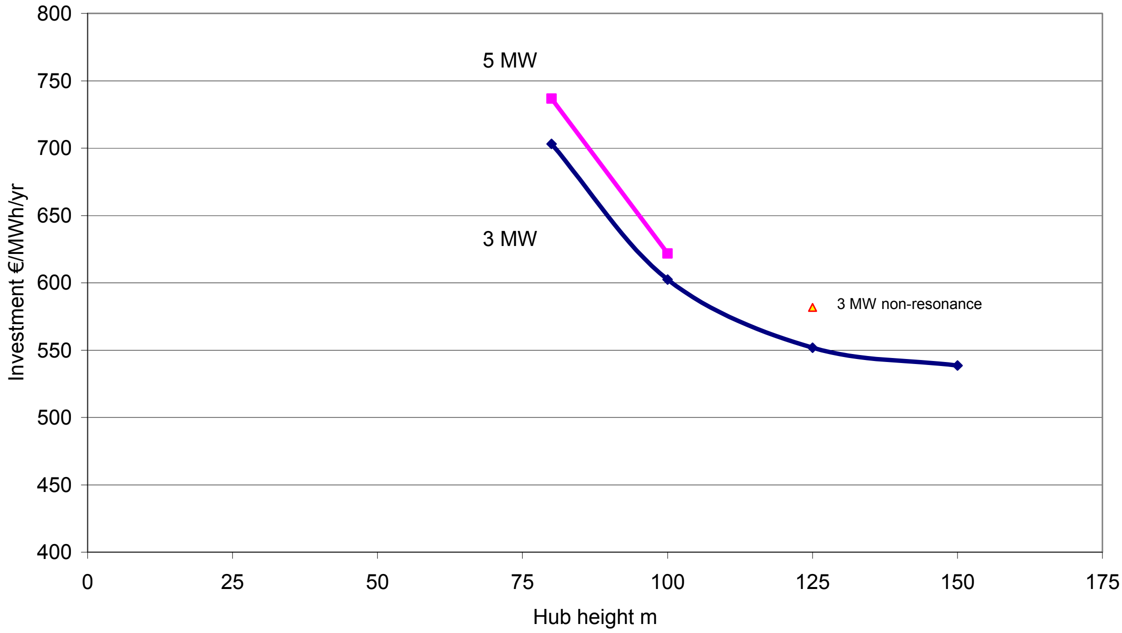

Figure 4. Summary of specific investment cost for 3 and 5 MW wind turbines furnished with welded steel shell towers, maximum diameter 4,5 m. Note that maximum 150 (100) m hub height was possible to reach with the limitation of the base diameter for 3 (5) MW turbines. The 3 MW 125 m tower is in resonance with the rotational frequency (1 p) and thus can not be used in reality. The outcome of the use of a non-resonance tower is shown as a separate data point. Based on Tables 9 - 10.

The specific investment cost for the different alternatives is summarized in Fig. 4 and is also revealed in Fig. 5 and Tables 9 - 10. The intended 175 m hub height alternative was not possible to attain with the 4,5 m base diameter limitation. In the 3 MW case the highest tower is 150 m, see Table 8, which demonstrates how a restriction on the base diameter influences the weight. For the 5 MW turbine the limit was 100 m. For all towers the maximum plate thickness is 75 mm. According to one source, some manufacturers experience difficulties above 50 mm.[17]

As mentioned earlier, for the 125 m case, the tower frequency happened to coincide with the rotational frequency, which means this tower in reality can not be used. For the purpose of this report it however seemed reasonable to utilize this data. Figures for a non-resonance tower are revealed as well, see Fig. 4 and Table 9.

Besides making the tower expensive, a small tower diameter also means difficulties with transferring the loads into the foundation and also with the distribution of the loads in the foundation.[18]

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[17] M. Hassanzadeh, T. Stalin and J. Johansson. High towers for wind power onshore – information dissemination. Vattenfall Reasearch and Development AB. 2008-12-05. P. 4.
[18] ibid

When studying the cost distribution as a function of the hub height in Fig. 5, the most striking feature is how even the distribution is, besides the natural

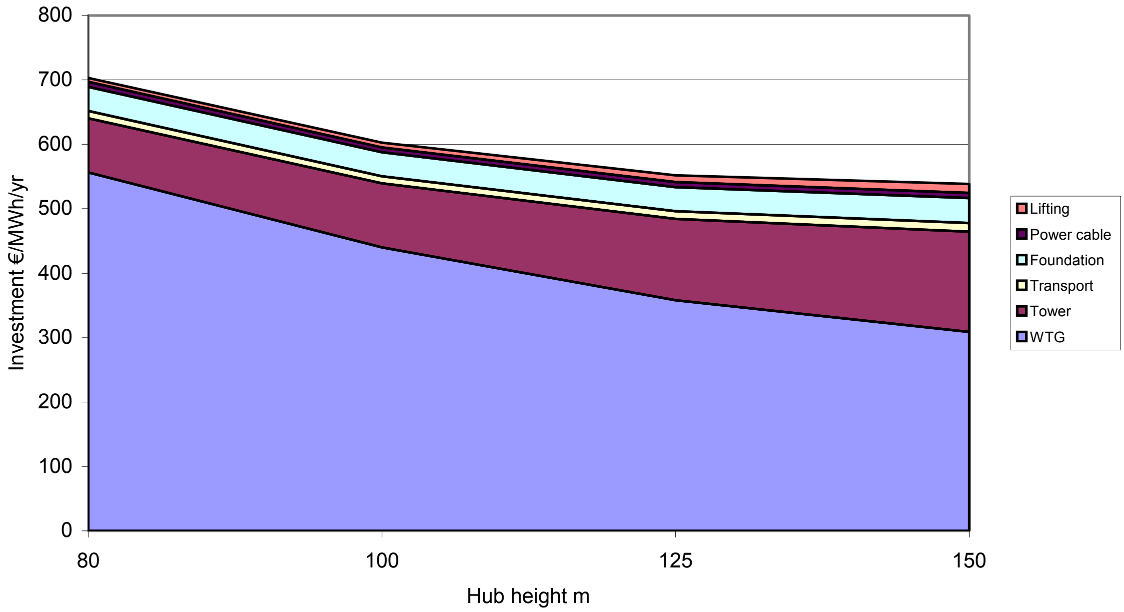

Figure 5. Cost distribution for 3 MW wind turbine with welded steel shell tower. For 125 m height the resonance tower is used.

effect of a lower specific WTG investment when production increases. Although the total specific investment decreases with increasing hub height, it is clear that the share of the tower cost is increasing.

Table 9. Weight and cost of 3 MW wind turbine with welded steel shell tower

Currrency exchange rate €/SEK		9,6		Hub height, m		
Tower		80	100	125***)	125	150
Diameter, top/base	m	3,0/4,5	3,0/4,5	3,0/4,5	3,0/4,5	3,0/4,5
Plate thickness, min/max	mm	15/34	15/43	15/59	15/75	15/75
Weight	t	182	274	425	521	610
Eigenfrequency	Hz	0,36	0,29	0,23	0,26	0,19
Stiff/soft (ref 3p)		soft	soft	res. 1p	soft	softsoft
Tower total	1000 €	419	630	978	1198	1404
Transportation						
Blades, hub, nacelle	1000 €	29	29	29	29	29
Tower	1000 €	29	42	65	78	92
Transportation total	1000 €	57	71	94	106	121
Lifting		crane	crane	crane	crane	crane
Heaviest lift	t	120	120	120	120	120
No crane hours (6 hours/lift)	h	32	36	40	40	46
Lifting total	1000 €	30	45	79	79	124
Foundation						
Foundation weight	t	1696	2121	2651	2651	3181
Foundation total (incl reinf., transp. moulds)	1000 €	187	233	292	292	350
Power cable in tower	1000 €	40	50	62	62	74
WTG price (less 80m ordinary steel shell tower)	1000 €	2783	2783	2783	2783	2783
Wind turbine installed total	1000 €	3516	3812	4288	4520	4855
Relative wind turbine investment*)		100%	108%	122%	129%	138%
Specific investment cost per MWh/year	€	703	602	552	582	539
Relative energy production investment**)		100%	86%	78%	83%	77%

*) Ref. 80 m tower

**) Ref. 3 MW, 80 m welded steel shell tower

***) Due to 1p resonance this tower can not be used. See text.

Hub height 175 m not possible with 4,5 m diameter limitation

Table 10. Weight and cost of 5 MW wind turbine with welded steel shell tower

Currrency exchange rate €/SEK 9,6		Hub height, m	
Tower		80	100
Diameter, top/base	m	3,8/4,5	3,8/4,5
Plate thickness, min/max	mm	52	68
Weight	t	278	389
Eigenfrequency	Hz	0,35	0,27
Stiff/soft		Soft	Soft
Tower total	1000 €	638	895
Transportation			
Blades, hub, nacelle	1000 €	90	90
Tower	1000 €	43	59
Transportation total	1000 €	133	150
Lifting		crane	crane
Heaviest lift	t	240	240
No crane hours (6 hours/lift)	h	36	40
Lifting total	1000 €	81	124
Foundation			
Foundation weight	t	2693	2121
Foundation total (incl reinf., transp. moulds)	1000 €	296	370
Power cable in tower	1000 €	66	83
WTG price (less 80m ordinary steel shell tower)	1000 €	4640	4640
Wind turbine installed total	1000 €	5855	6261
Relative wind turbine investment*)		100%	107%
Specific investment cost per MWh/year	€	737	622
Relative energy production investment**)		105%	88%

*) Ref. 80 m tower

**) Ref. 3 MW, 80 m welded steel shell tower

Hub heights 125 - 175 m not possible with 4,5 m diameter limitation

4.2 Steel shell tower with friction joints

The previous section clearly demonstrates that a restriction on the base diameter of a wind turbine tower has a detrimental effect on the weight and thus cost when reaching hub heights of 100 m and above. One way to get free of that restriction is to do away with the workshop welding and instead join the tower plates with screws and nuts, forming friction joints, performed in the field. This is also a way to reduce how the weldings detoriate the fatigue resistance of the steel. An example of a screw joint is revealed in Fig. 6.

An obvious problem of bolted connections is how to get access to the outer wall of the tower. One solution is to put the screws with nuts in advance in the outer, upper section of the tower and prepare the next section with long, slotted holes, see Fig. 7. Veljkovic and co-workers have investigated the behaviour of such connections.[19]

Another solution is depicted in Fig. 8 and 9.[20] Here the screws may be mounted from the inside, provided that the outside nut is held in place with some provisional arrangement. Note that the double friction plates provide a double lap joint, which is an ideal load path, although the number of nuts and screws gets high. Each tower section is assembled on the ground from near flat panels, which are easy to transport irrespective of tower diameter. The top sections, with a diameter allowing for transportation, are shipped assembled.

In the following calculations a joint arrangement with single lap joints, i.e. single load paths, is assumed. A friction coefficient of 0,35 is assumed.

Figure 6. Screw joint in the tower of a Fuhrländer 2,5 MW in Celle, Germany.

[19] Velkovic, Milan and Husson Wylliam. High-strength wind turbine steel towers. Elforsk rapport 09:11.
[20] Brochure Northstar wind towers, 2009. www.northstarwindtowers.com.

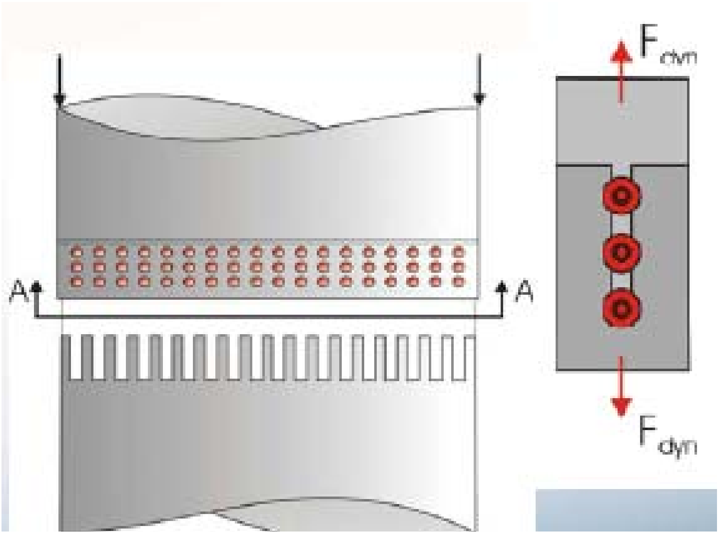

Figure 7. Principal design of a single lap tower joint according to Veljkovic.

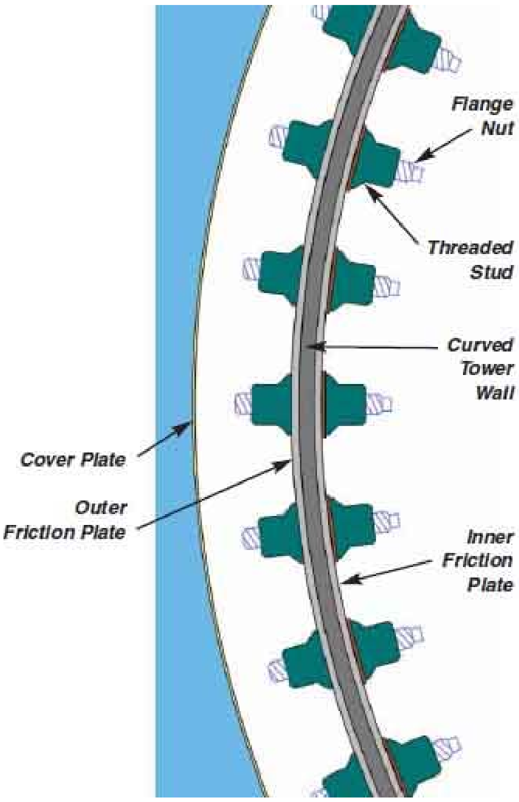

Figure 8. Double lap tower joint according to Northstar.

Figure 9. Wind turbine tower produced by Northstar, with bolted friction joints both in longitudinal and lateral directions.

Calculations were performed following the same procedure as for the welded towers, results depicted in Tables 11 – 12 and Fig. 10 - 12. The tendencies are in general the same as for the welded tower. Note that up to a hub height of 125 m the cost curves of the 3 and 5 MW turbines are almost identical. Direct comparisons between the various tower types will be carried out later in the report. In Fig. 11 and especially in Fig. 12 the influence of the high cost of the lifting towers may be noticed.

In Fig. 13 the comparison of the weight of friction towers with welded towers demonstrates the strong advantages of the friction type at high hub heights whereas it is nonexistent at 80 m hub height. For both sizes of wind turbines there is a minimum of the specific investment at hub heights of 125 – 150 m, with an obvious influence from the high cost of the use of lifting towers, due to the inability to use available cranes for the highest lifts. If not including the cost of lifting, the specific investment decreases all the way from 80 to 175 m hub height. As before, the calculated cost of the tower is a projected market cost including all material and work needed, such as steel plate, drilling, screws, nuts, painting etc. The cost of the completed product is assumed to be 2,50 €/kg.

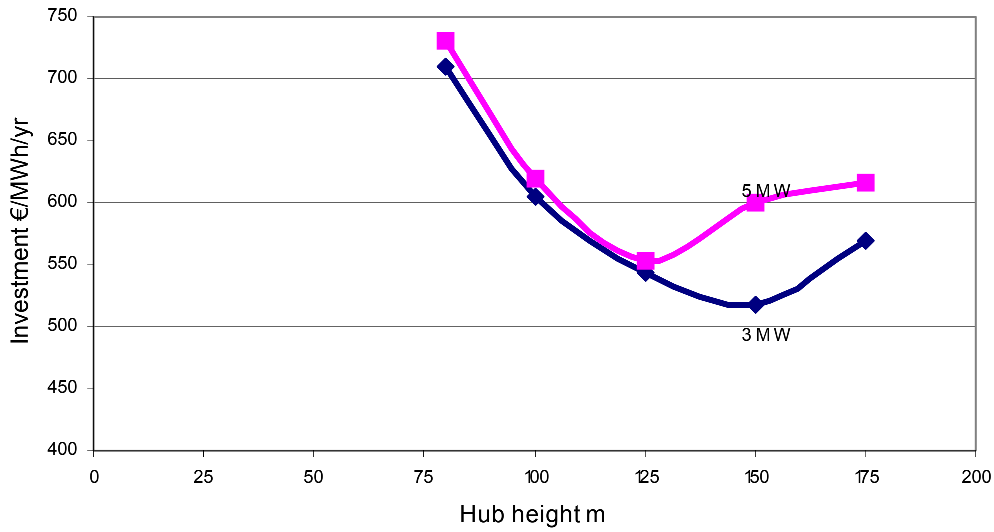

Figure 10. Summary of specific investment cost for 3 and 5 MW wind turbines with hub heights between 80 and 175 m, furnished with steel shell towers with friction joints. Based on Tables 11 – 12.

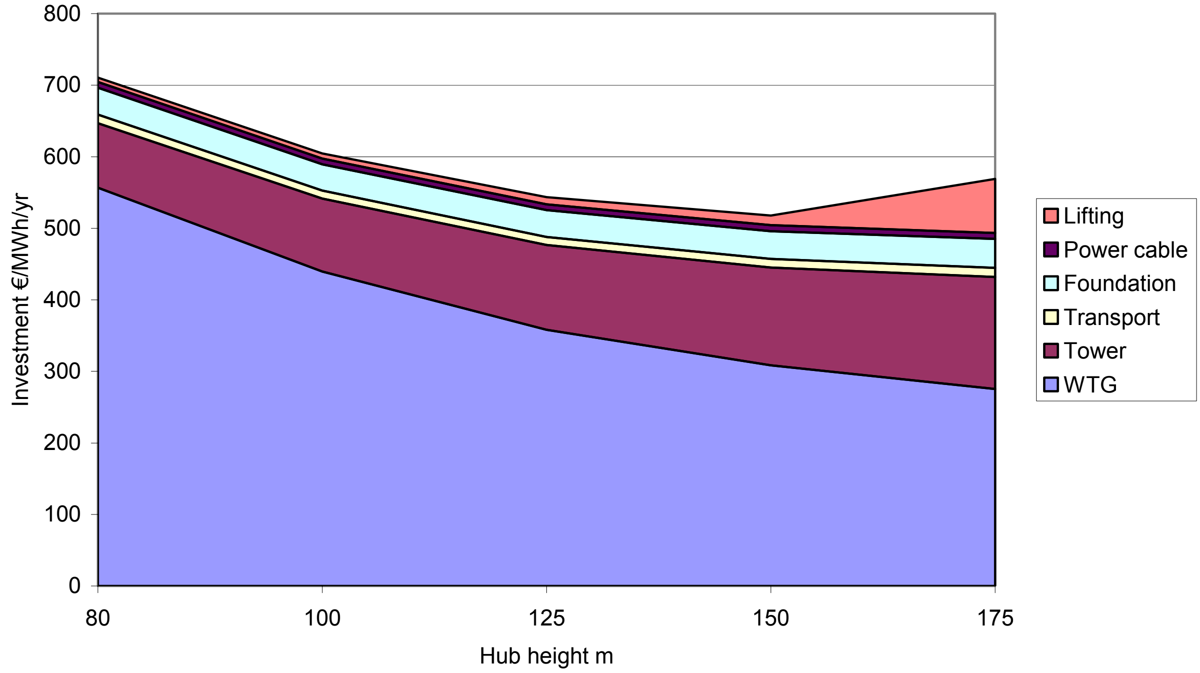

Figure 11. Cost distribution for 3 MW wind turbine with steel shell tower with friction joints

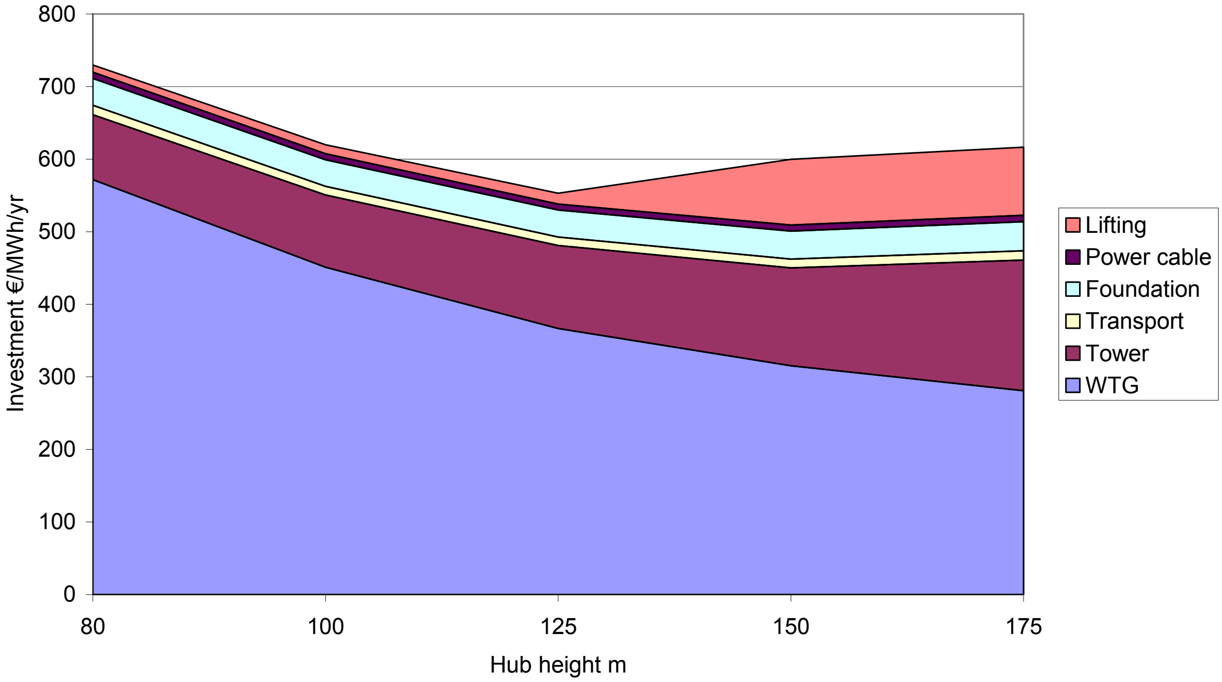

Figure 12. Cost distribution for 5 MW wind turbine with steel shell tower with friction joints

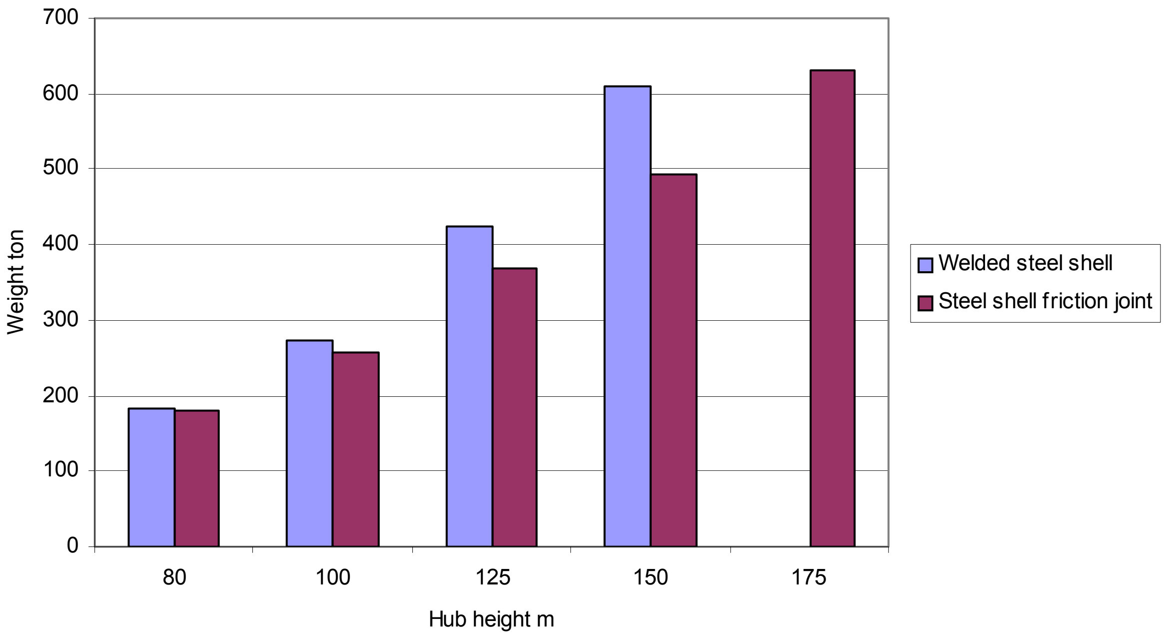

Figure 13. Weight of welded towers in comparison with friction joint towers for 3 MW turbines.

The main advantage of the friction joint towers is that they can be built without any restriction regarding the diameter. On the other hand, assembly at site may be expensive as well as regular checks of the pretension of the large number of bolts. The holes in the large steel panels need to be positioned with a high degree of accuracy, creating a need for specialized and heavy equipment.

In this chapter it is anticipated that all joints are performed as friction joints. In a real design the sections with a diameter of less than 4,5 meters may be designed partly with welded joints, if this provides any advantages.

Table 11. Weight and cost of 3 MW wind turbine with steel shell tower with friction joints

Currrency exchange rate €/SEK 9,60		Hub height, m				
Tower		80	100	125	150	175
Diameter, top/base	m	3,0/4,5	3,0/4,5	3,0/5,8	3,0/5,8	3,0/6,0
Plate thickness, min/max	mm	15/34	15/43	15/38	15/43	15/46
Weight	t	181	257	368	493	632
Eigenfrequency	Hz	0,36	0,29	0,26	0,20	0,17
Stiff/soft		soft	soft	soft	softsoft	softsoft
Tower total	1000 €	453	643	920	1233	1580
Transportation						
Blades, hub, nacelle	1000 €	29	29	29	29	29
Tower	1000 €	28	40	57	76	96
Transportation total	1000 €	57	69	86	105	126
Lifting		crane	crane	crane	crane	lift. towers
Heaviest lift	t	120	120	120	120	120
No crane hours (6 hours/lift)	h	32	36	40	46	
Lifting total	1000 €	30	45	79	124	760
Foundation						
Foundation weight	t	1696	2121	2651	3181	3711
Foundation total	1000 €	187	233	292	350	408
Power cable in tower	1000 €	40	50	62	74	87
WTG	1000 €	2783	2783	2783	2783	2783
Wind turbine installed total		3549	3822	4221	4668	5743
Relative wind turbine investment*)		100%	108%	119%	131%	162%
Specific investment cost per MWh/year	€	710	604	544	518	589
Relative energy production investment**)		101%	86%	77%	74%	81%

*) Ref. 80 m tower

**) Ref. 3 MW, 80 m welded steel shell tower

Table 12. Weight and cost of 5 MW wind turbine with steel shell tower with friction joints

Currrency exchange rate €/SEK 9,6		Hub height, m				
Tower		80	100	125	150	175
Diameter, top/base	m	3,8/5,8	3,8/6,4	3,8/7,0	3,8/7,6	3,8/9,2
Plate thickness, min/max	mm	20/36	20/38	20/40	20/45	20/52
Weight	t	285	401	566	777	1165
Eigenfrequency	Hz	0,40	0,32	0,26	0,22	0,22
Stiff/soft		soft	soft	soft	soft	soft
Tower total	1000 €	712	1002	1416	1942	2913
Transportation						
Blades, hub, nacelle	1000 €	90	90	90	90	90
Tower	1000 €	44	62	88	117	150
Transportation total	1000 €	134	154	177	207	240
Lifting		crane	crane	crane	lift. towers	lift. towers
Heaviest lift	t	240	240	240	240	240
No crane hours (6 hours/lift)	h	36	40	44		
Lifting total	1000 €	81	124	184	1302	1519
Foundation						
Foundation weight	t	2693	3367	4208	5050	5892
Foundation total	1000 €	296	370	463	555	648
Power cable in tower	1000 €	66	83	103	124	144
WTG price	1000 €	4542	4542	4542	4542	4542
Wind turbine installed total		5831	6273	6885	8673	10006
Relative wind turbine investment*)		100%	108%	118%	149%	172%
Specific investment cost per MWh/year	€	730	620	553	600	617
Relative energy production investment**)		104%	88%	79%	85%	88%

*) Ref. 80 m tower

**) Ref. 3 MW, 80 m welded steel shell tower

4.3 Pretensioned concrete tower

In a concrete tower (see e.g. Fig. 1) the concrete proper only withstands pressure. The ability to absorb tension is provided primarily by pretensioned tendons, located in ducts in the concrete or internal/external of the concrete walls. Putting them internal or external enables easy inspection. There are also traditional untensioned reinforcement bars cast into the concrete shell, necessary to provide the compressive strength.

A concrete tower is clearly dimensioned by the extreme load case, since it has large margins towards fatigue. It is assumed that the concrete is pretensioned by the tendons to 20 MPa. In the extreme load case the pressure side is off-loaded to close to zero whereas the tension on the other side is doubled.

By increasing the thickness of the concrete cover it may be possible to increase the lifetime to e.g. 50 years. One concrete tower may then serve for two generations of machineries, with obvious economical savings.

Compared to steel towers, concrete towers are much heavier and takes longer time to erect. On the other hand, the concrete or the concrete elements, if made small enough, are not subject to transportation restrictions, as for the case with welded steel towers with large base diameters.

K50 is a sufficient quality of the concrete needed.

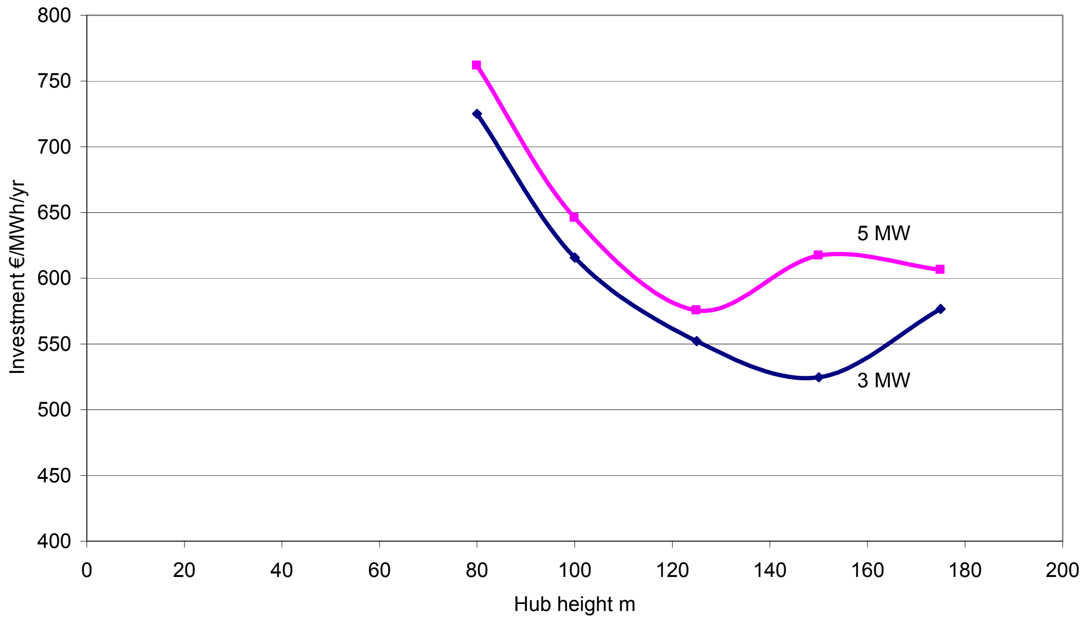

Figure 14. Summary of specific investment cost for 3 and 5 MW wind turbines furnished with slip formed concrete towers. Based on Tables 13 - 14.

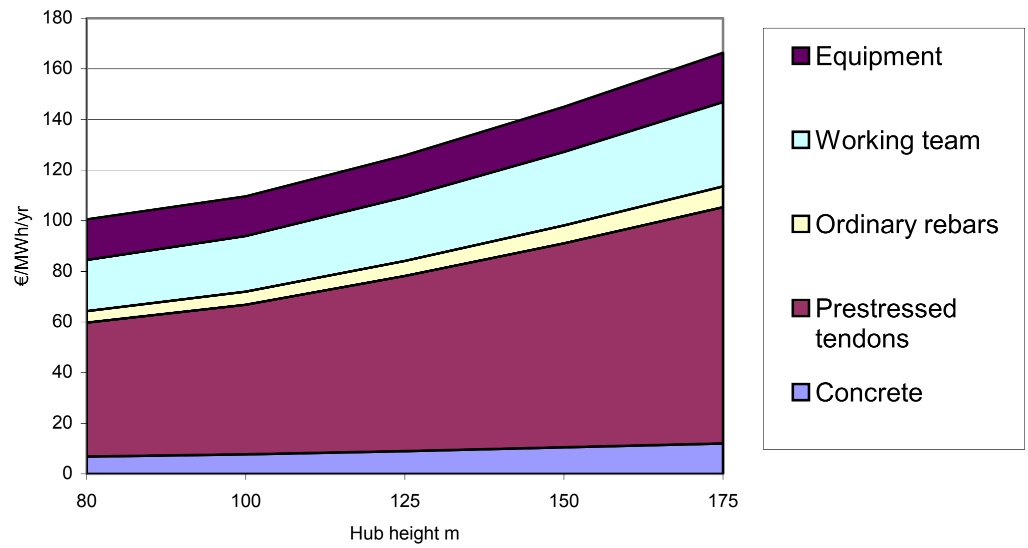

Figure 15. Cost distribution for a slip formed concrete tower designed for a 3 MW wind turbine.

Regardless if the tower is slip formed or assembled from precast elements, it is advantageous to install the post-stressing tendons from below, thus not needing to lift the heavy rolls of tendons to the tower top. Then it is however necessary to furnish the foundation with a cellar.[21]

4.3.1 Slip formed tower

In the basic case the tower shell is fabricated by slip forming, which is a continuous process running 24 hours a day until the tower is finished. The tendons are mounted and tensioned after the concrete has cured.

The cost distribution for a 3 MW slip formed tower in Fig. 15 reveals primarily that the tower cost, in relation to the production, is increasing with increasing hub height, although the specific investment cost was decreasing (up to a height of 150 m), see Fig. 14.

In Fig. 15 it is also clear that a quite large proportion of the cost is due to the prestressed reinforcement tendons, and that the relative amount even increases with increasing height. This is due to the fairly large amount of material, and especially to the high cost of this high-quality steel (7 €/kg), possibly at least partly due to a market lacking competition. Although the amount of concrete is large, the cost is low (0,06 €/kg). Also the cost of the ordinary, un-tensioned reinforcement is low (1 €/kg).

The concrete is either produced in an existing concrete factory or in a mobile plant erected for the purpose. The latter case presumes that the volume is

[21] M. Hassanzadeh, T. Stalin and J. Johansson. High towers for wind power onshore – information dissemination. Vattenfall Reasearch and Development AB. 2008-12-05. P. 7.

large enough. In the calculation a 150 km transport of the concrete is included.

Fabrication the slip formed towers in cold weather is not possible without warming.[22]

When comparing weight and cost of the towers according to Tables 13 - 14 with other known designs, it is evident that especially the amount of tendons is quite large. A close look however reveals that this is due to differences in

Figure 16. Moulds for production of concrete tower elements. Enercon.

load assumptions[23], which means that the objective of this study - to be able to compare different tower designs and hub heights - should still be possible to fulfil.

Slip forming implies a high degree of quality control regarding workmanship and climatological factors, e.g. precipitation and temperature.

[22] ibid p. 33

[23] Torbjörn Jonsson, NCC. Personal communication. 2010-06-04

4.3.2 Tower assembled from precast elements

By assembling a concrete tower from precast elements fabricated in a factory, it should be possible to achieve more stable conditions and thus a more even quality level, and also to reduce the excess costs associated with production at site.

The basic method for production of conical towers creates a need for a large number of moulds, see Fig. 16. Due to transportation reasons, wide elements close to the base are divided in two or three sections.

By CNC milling it may be possible to produce concrete elements featuring high tolerances, making assembly easier.[24]

In another method[25], the tower is assembled from identical corner elements with flat segments of varying width in between. In this way the number of moulds and elements is reduced, which should reduce the cost, especially when producing towers in low numbers.

A factory for the production of 60 000 m^3 of ring-shaped concrete tower elements a year, enough for 200 towers, is reported to cost 33 M€.[26]

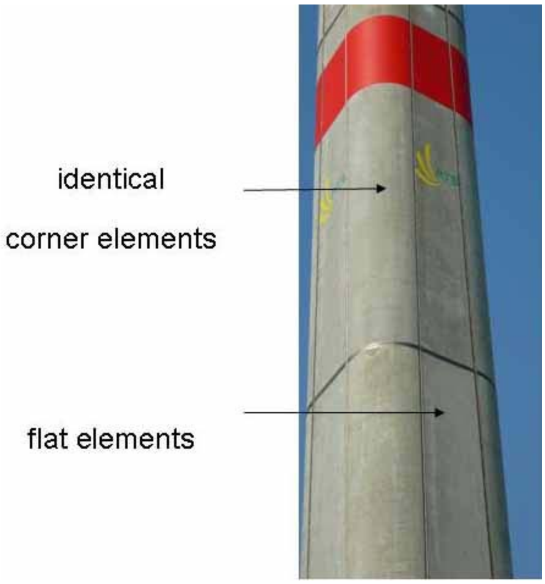

Figure 17. A concrete tower assembled from precast elements according to Advanced Tower Systems.

Figures from another reference indicate a manpower need of 150 for such a factory.[27] For the fabricated elements this indicates a cost per ton, which is an order of magnitude less than for the slip forming alternative. The assembly cost at site as well as tendons have to be added.

[24] M. Hassanzadeh, T. Stalin and J. Johansson. High towers for wind power onshore – information dissemination. Vattenfall Reasearch and Development AB. 2008-12-05.
[25] Advanced Tower Systems, www.advancedtowers.com
[26] M. Hassanzadeh, T. Stalin and J. Johansson. High towers for wind power onshore – information dissemination. Vattenfall Reasearch and Development AB. 2008-12-05. P. 9.
[27] Tower production launched in Viana do Castelo. Windblatt No 3 2008

The maximum economical transportation length is about 400 km.[28]

Table 13. Weight and cost of 3 MW wind turbine with concrete, slip formed tower

Currency exchange rate €/SEK	9,6	Hub height, m				
Tower		80	100	125	150	175
Diameter, base (top 3,0 m)	m	6,75	8	9,25	10,5	11,75
Concrete weight	t	603	829	1155	1527	1946
Weight prestressed reinforcement	t	39	54	75	99	126
Weight ordinary reinforcement	t	24	33	46	61	78
Concrete cost	1000 €	38	52	72	95	122
Prestressed reinforcement	1000 €	292	401	559	739	941
Ordinary reinforcement	1000 €	25	35	49	64	82
Working team 6 men (25 ton/24 hours)	1000 €	111	149	204	266	337
Equipment (mould, crane, pump etc)	1000 €	88	106	132	162	196
Tower total	1000 €	554	743	1016	1327	1677
Eigenfrequency	Hz	0,57	0,46	0,37	0,31	0,27
Stiff/soft		soft	soft	soft	soft	soft
Transportation						
Blades, hub, nacelle	1000 €	29	29	29	29	29
Concrete for tower	1000 €	35	48	66	88	112
Transportation total	1000 €	63	76	95	116	140
Lifting		crane	crane	crane	crane	lift. towers
Heaviest lift	t	120	120	120	120	120
No crane hours (6 hours/lift)	h	30	30	30	30	
Lifting total	1000 €	30	43	74	112	760
Foundation						
Foundation weight	t	1696	2121	2651	3181	3711
Foundation total	1000 €	187	233	292	350	408
Power cable in tower	1000 €	40	50	62	74	87
WTG	1000 €	2750	2750	2750	2750	2750
Wind turbine installed total	1000 €	3624	3895	4289	4729	5822
Relative wind turbine investment*)		100%	108%	118%	131%	161%
Specific investment cost per MWh/year	€	725	616	552	525	577
Relative energy production investment**)		102%	87%	78%	74%	81%

*) Ref. 80 m tower

**) Ref. 3 MW, 80 m welded steel shell tower

[28] M. Hassanzadeh, T. Stalin and J. Johansson. High towers for wind power onshore – information dissemination. Vattenfall Reasearch and Development AB. 2008-12-05. P. 34.

Table 14. Weight and cost of 5 MW wind turbine with concrete, slip formed tower

Currrency exchange rate €/SEK	9,6			Hub height, m		
Tower		80	100	125	150	175
Diameter, base (top 3,8 m)	m	7,8	8,8	10,1	11,3	12,6
Concrete weight	t	948	1286	1768	2310	2921
Weight prestressed reinforcement	t	62	84	115	150	190
Weight ordinary reinforcement	t	38	51	71	92	117
Concrete cost	1000 €	59	80	111	144	183
Prestressed reinforcement	1000 €	459	622	855	1117	1413
Ordinary reinforcement	1000 €	40	54	74	97	123
Working team 6 men (25 ton/24 h)	1000 €	169	226	307	398	501
Equipment (mould, crane, pump etc)	1000 €	116	143	181	225	274
Tower total	1000 €	897	1199	1630	2115	2661
Eigenfrequency	Hz	0,71	0,55	0,43	0,36	0,31
Stiff/soft		soft	soft	soft	soft	soft
Transportation						
Blades, hub, nacelle	1000 €	90	90	90	90	90
Concrete for tower	1000 €	55	75	105	139	177
Transportation total	1000 €	144	155	195	128	267
Lifting		crane	crane	crane	lift. towers	lift. towers
Heaviest lift	t	240	240	240	240	240
No crane hours (6 hours/lift)	h	30	30	30		
Lifting total	1000 €	78	117	170	1302	1519
Foundation						
Foundation weight	t	2693	3367	4208	5050	5892
Foundation total	1000 €	296	370	463	555	648
Power cable in tower	1000 €	66	83	103	124	144
WTG	1000 €	4542	4542	4542	4542	4542
Wind turbine installed total	1000 €	6023	6476	7103	8866	9782
Relative wind turbine investment*)			108%	118%	147%	163%
Specific investment cost per MWh/year	€	762	646	575	617	606
Relative energy production investment**)		108%	92%	82%	88%	86%

*) Ref. 80 m tower

**) Ref. 3 MW, 80 m welded steel shell tower

4.4 Concrete/steel hybrid tower

The idea behind building a hybrid concrete/steel tower is to use concrete in the wide lower part and steel in the upper part, where a conventional welded steel shell tower section may be designed without any risk of conflict with the transportation limitations. In reality it also makes it easier to design the concrete part and to get the eigenfrequencies right.

In this report the length of the steel section was to determined to be 50 meters for the 3 MW turbines and 40 meters in the 5 MW cases. In this way it was possible to stay within the 4,5 meter limit set. There may exist an additional cost for joining the concrete and the steel sections, which however is not included in the reported calculations.

Today hybrid towers are widely used by Enercon and also introduced by Advanced Tower Systems, see Fig. 18.

Figure 18. Siemens 2,3 MW wind turbine on a tower from Advanced Tower Systems

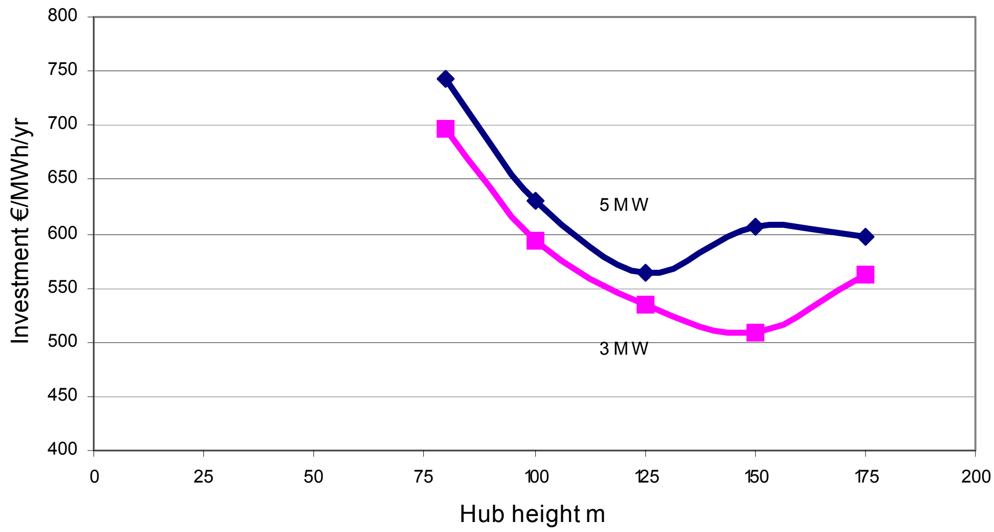

Figure 19. Summary of specific investment cost for 3 and 5 MW wind turbines furnished with hybrid concrete/steel towers. Based on Tables 15 – 16.

Table 15. Weight and cost of 3 MW wind turbine with hybrid concrete/steel tower

Currency exchange rate €/SEK	9,6		Hub height, m			
Concrete tower		80	100	125	150	175
Diameter, base (top 3,0 m)	m	6,75	8,00	9,25	10,50	11,75
Concrete weight	t	188	414	740	1112	1531
Weight prestressed reinforcement	t	12	27	48	72	100
Weight ordinary reinforcement	t	8	17	30	44	61
Concrete cost	1000 €	12	26	46	69	96
Prestressed reinforcement	1000 €	91	200	358	538	741
Ordinary reinforcement	1000 €	8	17	31	47	64
Working team 6 men (25 ton/24 h)	1000 €	42	80	134	197	267
Equipment	1000 €	55	73	99	129	162
Concrete tower total	1000 €	218	420	711	1044	1418
Eigenfrequency	Hz	0,48	0,45	0,40	0,36	0,32
Stiff/soft		soft	soft	soft	soft	soft
Steel tower						
Weight	t	84	84	84	84	84
Cost	1000 €	194	194	194	194	194
Transportation						
Blades, hub, nacelle	1000 €	29	29	29	29	29
Concrete for tower	1000 €	11	24	43	64	88
Steel tower	1000 €	14	14	14	14	14
Transportation total	1000 €	54	67	85	107	131
Lifting		crane	crane	crane	crane	lift. towers
Heaviest lift	t	120	120	120	120	120
No crane hours (6 hours/lift)	h	30	30	30	30	30
Lifting total	1000 €	30	43	74	112	760
Foundation						
Foundation weight	t	1696	2121	2651	3181	3711
Foundation total	1000 €	187	233	292	350	408
Power cable in tower	1000 €	40	50	62	74	87
WTG	1000 €	2750	2750	2750	2750	2750
Wind turbine installed total	1000 €	3472	3778	4168	4612	5789
Relative wind turbine investment*)		100%	108%	120%	133%	166%
Specific investment cost per MWh/year	€	695	594	537	514	569
Relative energy production investment**)		99%	84%	76%	73%	81%

*) Ref. 80 m tower

**) Ref. 3 MW, 80 m welded steel shell tower

Table 16. Weight and cost of 5 MW wind turbine with hybrid concrete/steel tower

Currency exchange rate €/SEK		9,6		Hub height, m		
Concrete tower		80	100	125	150	175
Diameter, base (top 3,0 m)	m	7,80	8,80	10,05	11,30	12,55
Concrete weight	t	289	627	1109	1651	2262
Weight prestressed reinforcement	t	19	41	72	107	147
Weight ordinary reinforcement	t	12	25	44	66	90
Concrete cost	1000 €	18	39	69	103	141
Prestressed reinforcement	1000 €	140	303	537	799	1094
Ordinary reinforcement	1000 €	12	26	47	70	95
Working team 6 men (25 ton/24 h)	1000 €	59	115	196	287	390
Equipment	1000 €	63	90	129	172	221
Concrete tower total	1000 €	308	611	1041	1526	2072
Eigenfrequency	Hz	0,59	0,53	0,47	0,41	0,36
Stiff/soft		soft	soft	soft	soft	soft
Steel tower						
Weight	t	130	130	130	130	130
Cost	1000 €	298	298	298	298	298
Transportation						
Blades, hub, nacelle	1000 €	90	90	90	90	90
Concrete for tower	1000 €	17	36	64	95	130
Steel tower	1000 €	20	20	20	20	20
Transportation total	1000 €	127	146	174	205	240
Lifting		crane	crane	crane	lift. towers	lift. towers
Heaviest lift	t	240	240	240	240	240
No crane hours (6 hours/lift)	h	35	35	35	35	35
Lifting total	1000 €	78	117	170	1302	1519
Foundation						
Foundation weight	t	2693	3367	4208	5050	5892
Foundation total	1000 €	296	370	463	555	648
Power cable in tower	1000 €	66	83	103	124	144
WTG	1000 €	4542	4542	4542	4542	4542
Wind turbine installed total	1000 €	5715	6167	6792	8552	9464
Relative wind turbine investment*)			108%	119%	150%	166%
Specific investment cost per MWh/year	€	719	612	548	593	585
Relative energy production investment**)		102%	87%	78%	84%	83%

*) Ref. 80 m tower

**) Ref. 3 MW, 80 m welded steel shell tower

4.5 Lattice tower

Lattice towers have been used in large numbers for smaller wind turbines, especially in non-European countries. For larger turbines they have mainly been a choice when a stiff (under-critical) tower was needed.

It is clear that they often are considerably lighter than towers based on other technologies. The physical background to this phenomenon is the large widths of the lower sections. The need for material to take strain or pressure is inversely proportional to the width. With a tubular section a thin-walled construction will finally meet with buckling, which restrains the maximum diameter. A lattice design does not buckle like a shell. The risk of buckling of the individual members is controlled by inserting numerous struts that give the lattice tower its characteristic look.

The Finnish company Ruukki is introducing a further developed design of lattice towers based on use of hexagonal steel profiles and high strength steel, enabling lower weights and better economy.[29]

The German wind turbine manufacturer Fuhrländer use lattice towers for attaining very high hub heights. For such applications the following qualities are claimed:[30]

[29] Reaching the heights with Ruukki. Sales presentation. Ruukki Engineeering. June 14 2010.

[30] M. Hassanzadeh, T. Stalin and J. Johansson. High towers for wind power onshore – information dissemination. Vattenfall Research and Development AB. 2008-12-05. P. 16.

Figure 20. A Fuhrländer 2,5 MW wind turbine with 100 m turbine diameter and a lattice tower providing 141 m hub height. Photo Vattenfall.

- Low weight and price
- Used since a century
- Utilisation of standard hot-dip galvanized profiles
- Visual transparency
- Favourable when access is difficult
- Less provisions for disassembly and disposal

On the other hand, there are also some disadvantages:

- A high number of bolts, exposed to the open air, and in need of periodic checks
- Sometimes problematic dynamic properties and torsional stiffness

For a 141 m lattice tower for a 2,5 MW wind turbine (see Fig. 20) the number of bolts was 13 000. The cost of checking and post-stressing these bolts has been estimated at 3000 € per year.[31] As mentioned, maintenance cost is not included in this report.

[31] ibid p. 14.

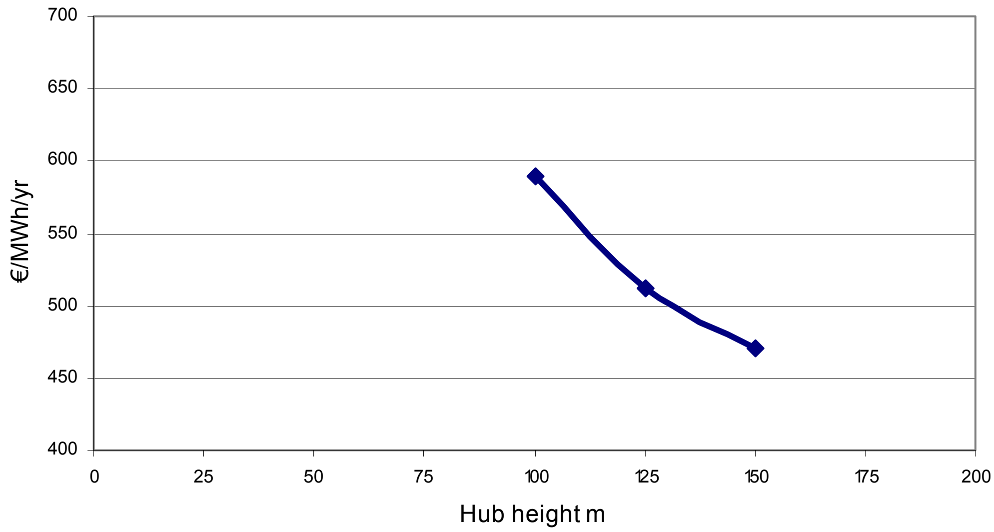

Figure 21. Specific investment cost for 3 MW wind turbine furnished with lattice towers. Based on Table 17.

The visual qualities are controversial, especially due to the resemblance to towers for high-voltage power lines, generally claimed to be ugly.

An open design, like a lattice tower, is more prone to icing than a tubular tower. The possible impact on the dynamic properties may be the most severe consequence, which may endanger the wind turbine in an extreme case. It may also be a problem for maintenance personnel, even if their elevator runs on heated rails. Another danger is the increased risk of falling ice.

The last resort for evacuating a wind turbine nacelle is normally by a rope to the ground. The numerous struts of a lattice tower here may present an additional danger.

One stated advantage of lattice towers is that they should have less aerodynamic drag and hence create less tower shadow and noise. This is however questionable. The probably noisiest wind turbine ever built was the 2 MW GE Mod-1 from the early 1980s. Its down-wind turbine was erected on a quite sturdy lattice tower.[32]

As mentioned, proponents of lattice towers claim that they need small areas for the assembly. On the other hand, the normal procedure seems to be to assemble the tower lying on the ground before raising, which implies need of an area at least as long and wide as the tower itself. A width at the base of e.g. 30 m is quite considerable.

[32] H. H. Hubbard, K. P. Shepherd. Wind Turbine Acoustics. In D. A. Spera (ed.). Wind Turbine Technology. ASME Press 1994. P. 393.

In Table 17 the data for lattice towers for 3 MW turbines with 100, 125 and 150 m hub height is depicted. The designs are based on the layout of an existing lattice tower. Eigenfrequencies have not been calculated due to the extensive work needed for doing this for lattice towers. Since the separate steel members for a lattice tower enables an efficient transportation, the tower transportation cost has been halved compared with the figures used for tubular towers. On the other hand, the assembly is very time-consuming, which justified a doubling of the normal lifting/assembly cost. Although the basic material is low-cost, the need for a specialized machine for cutting and drilling warrants the same cost as for the welded towers (2,3 €/kg).

Table 17. Weight and cost of 3 MW wind turbine with lattice tower

Currency exchange rate €/SEK	9,6		Hub height, m		
Tower		100	125	150
Width, top/base	m	2/20	2/25	2/30
Weight	t	247	307	369
Eigenfrequency	Hz		not calculated	
Stiff/soft		-	-	-
Tower total	1000 €	568	706	849
Transportation				
Blades, hub, nacelle	1000 €	30	30	30
Tower	1000 €	19	24	29
Transportation total	1000 €	50	55	60
Lifting		crane	crane	crane
Heaviest lift	t	120	120	120
No crane hours (6 hours/lift)	h	36	40	46
Lifting total	1000 €	45	79	124
Foundation				
Foundation weight	t	2121	2651	3181
Foundation total (incl reinf., transp. moulds)	1000 €	233	292	350
Power cable in tower	1000 €	50	62	74
WTG price (less 80m ordinary steel shell tower)	1000 €	2783	2783	2783
Wind turbine installed total	1000 €	3729	3977	4240
Relative wind turbine investment*)		-	-	-
Specific investment cost per MWh/year	€	590	512	470
Relative energy production investment**)		93%	81%	74%

*) Ref. 80 m tower (not calculated)

**) Ref. 3 MW, 80 m welded steel shell tower

4.6 Wooden tower

Wood has been used as a construction material for wind turbine blades for decades, but only recently considered for wind turbine towers. This may seem strange, since towers should be a less demanding application than blades. And wood is in general known to be an economical construction material resistant to fatigue and buckling.

The only known large wind turbine tower of wood is the one designed by Timber Tower in Germany, see Fig. 22. It seems to be built of "KL-" panels from Martinsons Byggsystem, Bygdsiljum. "KL" stands for Swedish "korslimmat", i.e. cross glued, which is used instead of the more commonly known glue-laminated wood or glulam, which is rather sensitive to moisture. It withstands roughly 10 MPa and has a density of 460 kg/m^3. The price for KL-panels in large quantities is about 0,9 €/kg.[33] In this report a price of the completed tower of 1,2 €/kg has been assumed.

Figure 22. A wooden tower built by Timber Tower, Germany,[34] for a Vensys 1,5 MW wind turbine. Left a wooden panel lifted during the assembly, right the tower finished.

[33] Håkan Risberg, Martinsons Byggsystem. E-mail 2010-03-25.
[34] www.timbertower.de

In Table 18 rough data of 100 and 125 m wooden towers for 3 MW turbines are presented. The towers are considered to be homogenous, i.e. no consideration has been given to how to join the wooden panels laterally and longitudinally. Note the substantial wall thickness, almost half a metre, which decreases the risk of buckling. Due to the large areas involved, it may be possible to simply glue the panels to each other, with slanted joints in the longitudinal direction. It also seems practical to assemble a tower in 10 – 20 m long tubular segments, standing upright vertically, complete with ladders and work platforms, before lifting. In that way, the probably costly provisional inner structure seen in Fig. 22 can be avoided. The largely flat panels are assumed to be transported in a compact way, utilizing the vehicles efficiently and resulting in the same transportation cost as used for the friction joint towers.

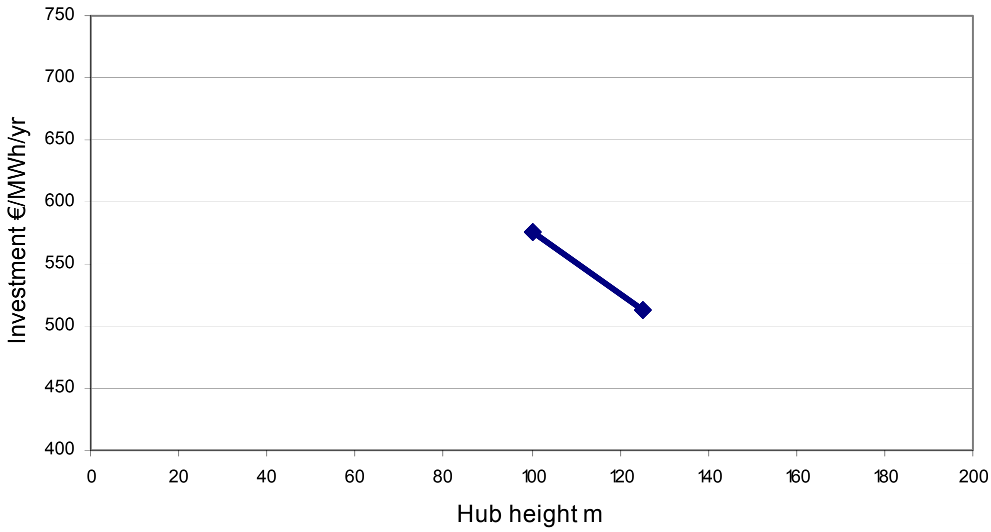

Figure 23. Specific investment cost for 3 MW wind turbine furnished with wooden towers. Based on Table 18.

Table 18. Weight and cost of 3 MW wind turbine with wooden tower

Currency exchange rate €/SEK 9,6		Hub height, m	
Tower		100	125
Diameter, top/base	m	3,0/9,0	3,0/10,0
Wall thickness,	mm	450	450
Weight	t	415	594
Eigenfrequency	Hz	0,32	0,26
Stiff/soft		soft	soft
Tower total	1000 €	498	712
Transportation			
Blades, hub, nacelle	1000 €	30	30
Tower	1000 €	40	56
Transportation total	1000 €	72	89
Lifting		crane	crane
Heaviest lift	t	120	120
No crane hours (6 hours/lift)	h	36	40
Lifting total	1000 €	45	79
Foundation			
Foundation weight	t	2121	2651
Foundation total	1000 €	233	292
Power cable in tower	1000 €	50	62
WTG	1000 €	2750	2750
Wind turbine installed total	1000 €	3648	3984
Relative wind turbine investment*)		-	-
Specific investment cost per MWh/year	€	576	513
Relative energy production investment**)		82%	73%

*) Ref. 80 m tower (not calculated)

**) Ref. 3 MW, 80 m welded steel shell tower

5 Comparisons and conclusions

The main evaluation criterion used in this report was the investment of a commissioned wind turbine divided by the yearly production, in this report called the specific cost. This means that no consideration was given to balance of plant costs such as site, roads and grid connection. Neither was any consideration given to maintenance costs. Since none of these costs is expected to vary in direct proportion to the tower height, the way of calculation in general will restrain the optimal hub height. On the other hand, the high cost of the largest cranes may increase the maintenance cost.

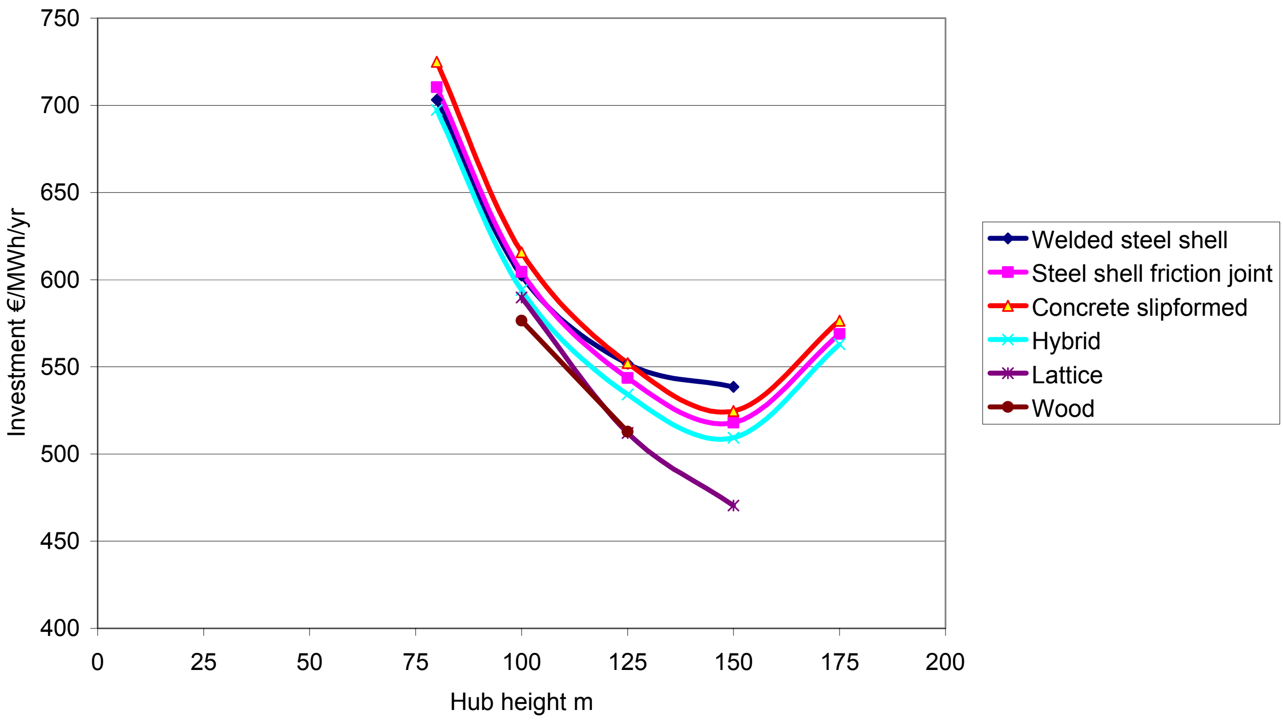

Figure 24. Summary of tower alternatives for 3 MW wind turbines.

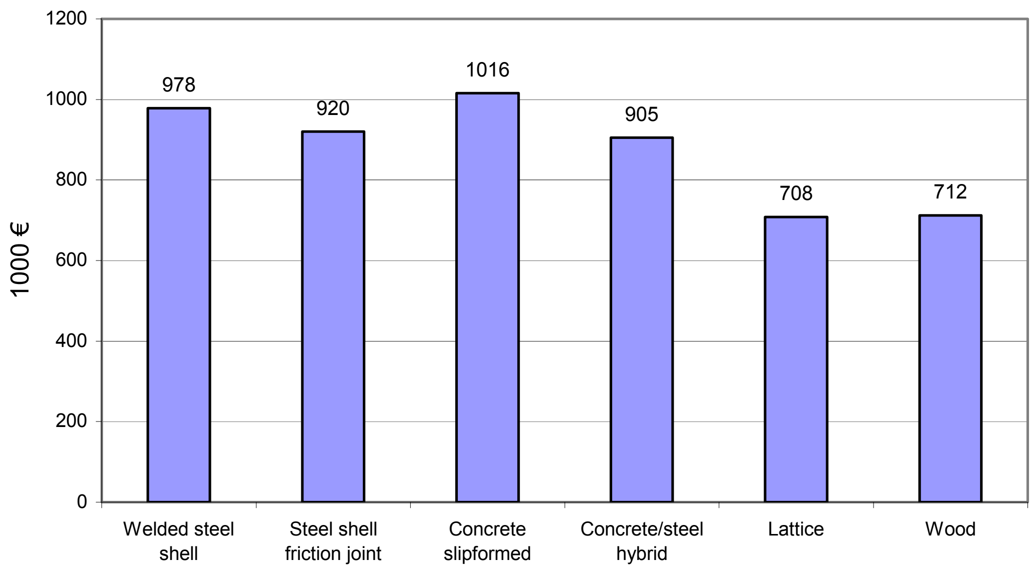

Figure 25. Tower cost only for the alternative designs. Power 3 MW, hub height 125 m.

For the 3 MW turbines Fig. 24 initially reveals reduced investment costs in relation to the electricity production up to a hub height of 150 m. The increase of costs at 175 m height depends, as mentioned earlier, on the transfer to lifting towers for lifting. They will also influence the cost of major maintenance operations.

At heights up to 100 m the cost of the different alternatives follow each other closely. At 125 m height the welded steel tower reveals a deviation towards higher relative cost. This tendency is even stronger at 150 m height, and it was not possible to design a welded steel tower for a hub height of 175 m. These tendencies are well explain by the need to restrain the base diameter to 4,5 m due to transportation.

The previous figure contains data on the total wind turbine investment, of which the tower amounts to about 20 %. A closer comparison of the tower cost only is made in Fig. 25, revealing data for 125 m hub height. The alternatives comes out in the order Concrete slip formed - Welded steel shell – Steel shell friction joint – Concrete/steel hybrid – Wood – Lattice, where the lattice tower costs 30 % less than the most expensive alternatives. This means that the differences are significant. A more specific comparison between welded steel shell towers and ditto with friction joints was provided in Fig. 13 in a previous chapter. From this study one can also draw a quite firm conclusion that hybrid towers generally are more economical than pure concrete ones.

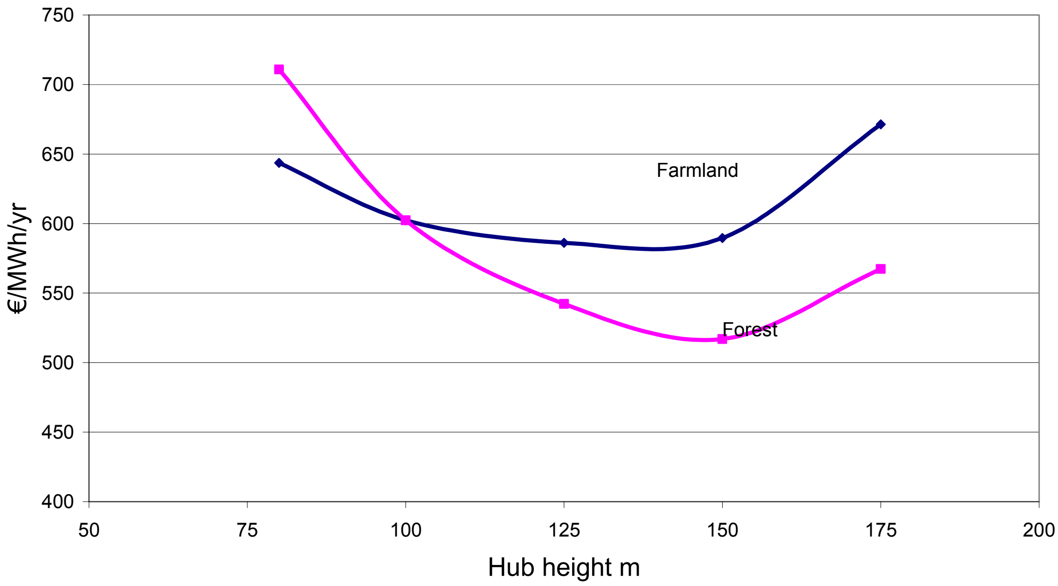

Figure 26. Specific investment when siting a 3 MW wind turbine with friction joint towers in forest (wind shear exponent 0,33) and in open farmland (exponent 0,20), in both cases with a mean wind speed of 6,2 m/s at a height of 100 m.

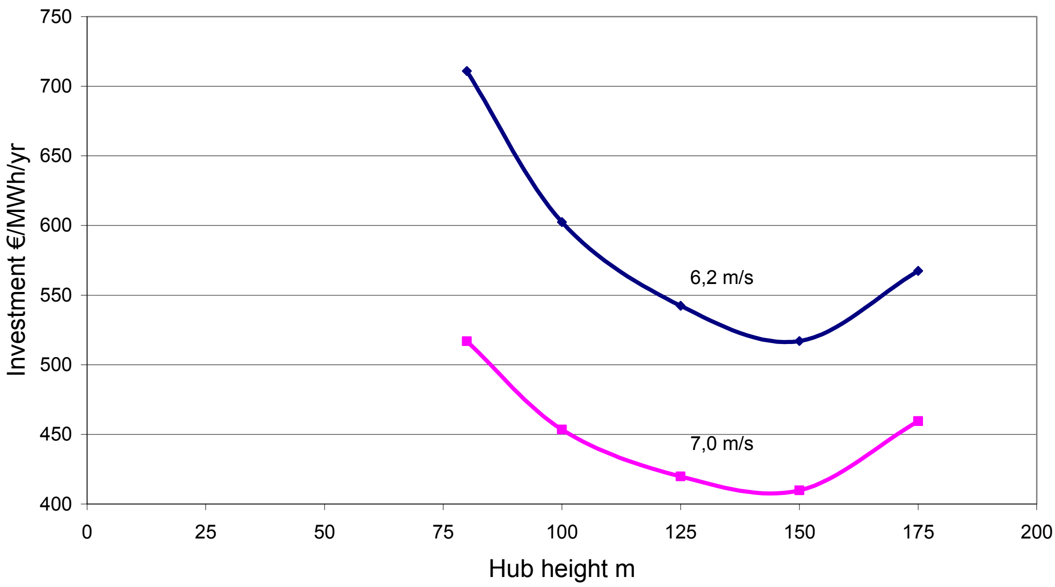

Figure 27. Specific investment when siting a 3 MW wind turbine with friction joint towers in forest (wind shear exponent 0,33) with a mean wind speed at a height of 100 m of 6,2 m/s or 7,0 m/s.

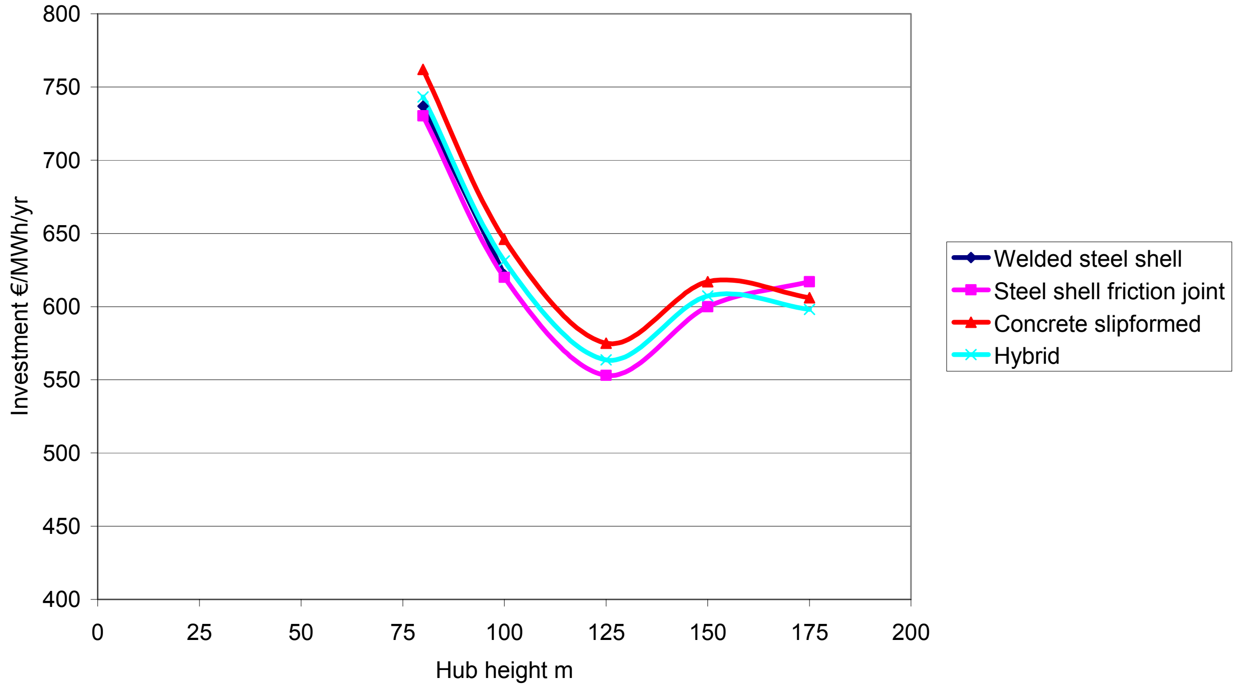

Figure 28. Summary of tower alternatives for 5 MW wind turbines.

Another question to address is whether towers should be built higher in forests than in the open farmland, where an important difference is the higher wind shear. Fig. 26 reveals the decrease of cost with increasing hub height is more pronounced in the forest case with its higher wind shear. Knowing that the cost increase above 150 m was due to the use of lifting towers, the optimum may be shifted further upwards if and when a more economical lifting technology is available. Please also note that this comparison is made under the presumption that the mean wind speed at a height of 100 m is the same for both locations. The higher wind shear above the forest then means that it is windier at a height of e.g. 150 m above the forest than above the farmland, which may otherwise seem unlikely.

A supplementary question is if the tendencies change when a windier site is available. Fig. 27 presents no clear answer on that question.

Looking at 5 MW turbines, Fig. 28 demonstrates that the different tower alternatives follow each other rather closely. As mentioned previously, the cost increase above 125 m is due to the transition to lifting towers. Since it was not possible to build higher welded steel shell towers for 5 MW turbines than 100 m, they do not differ visibly as in the 3 MW comparisons.

From the figures in this chapter it is not easy to recognize any difference in the cost level between 3 and 5 MW turbines. However, previously depicted figures, such as Fig. 10, 14 and 19, demonstrate that the cost level of the 5 MW alternatives in general are higher than that of the 3 MW turbines, although one should point out that this may not be valid with future turbines.

A final question regards if there are any differences in the land use, i.e. in the amount of forest that has to be cleared for the transportation and erection procedures. Regarding the choice of tower type, the differences seem to be small. There are varying views regarding lattice towers. It is however clear that the largest mobile cranes need large areas both for the lifting procedure and for the travelling between the individual sites. Land need for lifting towers is much smaller. On the other hand, this technology is so far quite expensive.

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