# LIFE CYCLE ASSESSMENT FOR TRANSMISSION TOWERS

**A comparative study of three tower types**

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**EXTRACT**

Statnett is developing prototypes for new types of transmission towers, aluminium towers and guyed M-towers. The report identifies environmental impacts of these towers from a life cycle perspective, including a comparison with the current standard steel transmission tower. The main findings of the study are that aluminium towers and guyed M-towers have significantly lower net impacts than standard steel towers in seven environmental impact categories. When impacts are assessed in terms of a 2-km transmission line section, conductors and transmission losses become the largest contributors to environmental impacts in most categories.

The study highlights the importance of sustainable material sourcing for tower manufacturing and the benefits of recycling to minimize negative impacts on the environment. The information provided can prove useful for strategic decisions at Statnett, e.g. for design and procurement decisions. The study and life cycle inventory provides a basis for further analyses or comparisons.

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## SUMMARY

Statnett is developing prototypes for two types of electric transmission towers. As part of its sustainable system development, the company seeks to obtain knowledge on the environmental impacts associated with these new towers to support the decision-making process. Life cycle assessment (LCA) is a methodology to assess the environmental impacts of products or services throughout their life cycle. Hence, a range of impacts on the environment are evaluated from resource extraction to material production, product manufacturing, use of the product up to its disposal, including production wastes. The general procedure of conducting an LCA is standardised in ISO 14040 and ISO 14044 and results can therefore be compared to similar products or services.

In the study, a comparison is made between Standard steel transmission towers and two prototypes currently under development, Aluminium towers and guyed M-towers. Three main comparisons are made;

- Aluminium tower vs. Standard steel tower, in mountainous terrain
- Guyed M-tower vs. Standard steel tower, in flat terrain
- Concrete vs. steel foundations for a Standard steel tower, in flat terrain

The two first scenarios are compared as a) stand-alone objects, i.e. one tower and its foundations, and b) in terms of a 2-km section of a transmission line, including transmission components such as conductors, insulators, earth and shield wires. The assessment is a cradle to grave analysis, including raw material extraction, manufacturing of components, construction, operation and maintenance during a 70 year service life and material retrieval and recycling at the end of life. The inventory used for the study was based on high quality data from international databases, data from tower manufacturers and design data from EFLA and Statnett.

The assessment provides numerical results on the environmental impacts for seven environmental impact categories, where the contribution of each life cycle stage and different components of the system to each impact category is identified. The impact categories are: global warming, ozone depletion, photochemical ozone formation, acidification, eutrophication, abiotic depletion (elements) and abiotic depletion (fossil).

The main findings of the study are the following;

- Aluminium towers have a significantly lower net impact than Standard towers in all seven impact categories.
- In the global warming impact category, the net impact of the Aluminium tower is 43% lower than the Standard steel tower.
- Guyed M-towers have a lighter structure than Standard steel towers, with fewer foundations, and have significantly lower net impacts in all seven impact categories.
- In the global warming impact category, the net impact of the M-tower is 48% lower than the Standard steel tower.
- Recycling of aluminium and steel is a significant impact factor in all impact categories.

- Standard steel towers with prefabricated steel foundations and concrete foundations have similar net impacts in four impact categories, assuming the retrieval of steel foundations and their recycling.
- By excavating and recycling steel foundations, net carbon footprint saving of 6 tonnes $CO_2$-equivalents per tower can be achieved.
- When environmental impacts of the above tower types are assessed in terms of a 2-km transmission line section, conductors and transmission losses become the largest contributors to environmental impacts in five of seven categories. Aluminium and M-towers have net impacts similar to Standard towers in most categories, but significantly lower impacts in 2-3 categories.
- In the global warming impact category, a 2-km section with Aluminium towers has a 4% lower net carbon footprint than the section with Standard steel towers. A 2-km section with M-towers has a 7% lower impact than the section with Standard steel towers.

The study highlights the importance of sustainable material sourcing, particularly steel and aluminium used for tower manufacturing, and the benefits of recycling. Informed sourcing of materials for tower manufacturing is critical in minimizing environmental impacts of the tower structure. Primary production of steel and aluminium manufacturing is both material and energy intensive and improved management of natural resources delivers real benefits, not only for the environment but also for society, economy and human health, reducing the need for primary production.

The results of this study are useful in targeting areas where improvement can be made, providing knowledge to be able to integrate climate and environmental aspects into the decision-making process. LCA can thus serve as a powerful tool in environmental management systems, fulfilling new requirements of the ISO 14001:2015 standard which requires an integration of life cycle thinking to all stages of an organization's activities; from design and development stages, procurement, operation and maintenance to end of life stages. This implies not only ensuring that the upstream supply chain is practicing the same habits, but also ensuring sustainable management of resources at the end of a product's service life.

The information provided in this study can hence prove useful for strategic decisions at Statnett, e.g. design decisions and procurement decisions to minimize negative impacts on the environment. The results also provide insight into benefits of material recovery and recycling at the end of the towers' life cycle. The study and life cycle inventory also provides a basis for further analyses or comparisons.

# SAMMENDRAG

Statnett utvikler nå prototyper for to typer elektriske transmisjonsmaster. Som en del av sin bærekraftig systemutvikling, ønsker selskapet å skaffe seg kunnskap om miljøpåvirkningen knyttet til disse nye mastene for å støtte beslutningsprosessen. Livscyklusvurdering (LCA) er en metode for å vurdere miljøpåvirkningen av produkter eller tjenester gjennom hele livssyklusen. Derfor vurderes en rekke miljøpåvirkninger fra ressursutvinning til materialproduksjon, produktfremstilling, bruk av produktet, til deres disposisjon, inkludert produksjonsavfall. Den generelle prosedyren for å gjennomføre en LCA er standardisert i ISO 14040 og ISO 14044, og resultatene kan derfor sammenlignes med lignende produkter eller tjenester.

I studien er det gjort en sammenligning mellom standard stålmast og to prototyper som for tiden er under utbygging, aluminiums mast og utvendig bardunert M-mast. Tre hoved sammenligninger er gjort;

- Aluminiums mast vs. Standard stålmast, i bratt terreng (fjellterreng)
- Bardunert M-mast vs. Standard stålmast, i flatt terreng
- Betong fundamenter vs. stålfundamenter for en standard stålmast, i flatt terreng

De to første scenariene sammenlignes a) som frittstående objekter, det vil si en mast og dens fundamenter, og b) i form av en 2 km seksjon av en kraftledning, inkludert overføringskomponenter som faseliner, isolatorer, toppline og jordingstråd. Vurderingen er en livsløpsanalyse, som inkluderer utvinning av råmaterialer, produksjon av komponenter, konstruksjon, drift og vedlikehold i løpet av en 70-års levetid og til slutt materialinnhenting og resirkulering. Opplysningene som ble brukt til studien, var basert på høykvalitetsdata fra internasjonale databaser, data fra masteprodusenter og design-data fra EFLA og Statnett.

Vurderingen gir numeriske resultater på miljøpåvirkningen for syv miljøkonsekvenskategorier, hvor bidraget fra hvert livssyklusstadium og ulike komponenter i systemet til hver påvirkningskategori identifiseres. Påvirkningskategoriene er: globaloppvarming, nedbrytning av ozonlaget, fotokjemisk smog, sur nedbør, eutrofiering, abiotisk utarming (elementer) og abiotisk utarming (fossil).

Hovedfunnene i studien er følgende;

- Aluminiummaster har en betydelig lavere nettopåvirkning enn standardmastene i alle syv påvirkningskategoriene.
- I den globale oppvarmingskategorien har aluminiummaster 43% lavere nettokarbonavtrykk enn standard stålmaster.
- Bardunerte M-master har en lettere struktur enn Standard stålmaster, med færre fundamenter, og har betydelig lavere nettopåvirkning i alle syv påvirkningskategoriene.
- I den globale oppvarmingskategorien, er M-mastens nettopåvirkning 48% lavere enn Standard stålmastens.
- Gjenvinning av aluminium og stål er en betydelig faktor i alle påvirkningskategoriene.

- Standardstålmaster med prefabrikkerte stålfundamenter og betongfundamenter har tilsvarende nettopåvirkning i fire påvirkningskategorier, forutsatt demontering av stålfundamenter og gjenvinning av disse.
- Ved demontering og gjenvinning av stålfundamenter kan det oppnås en utslippsbesparelse på 6 tonn $CO_2$-ekvivalenter per mast.
- Når miljøpåvirkningen av de ovennevnte mastetypene vurderes i forhold til en 2 km kraftledning, blir faseliner og overføringstap de største bidragsyterne til miljøpåvirkning i fem av syv kategorier. Aluminium og M-master har nettopåvirkning tilsvarende Standard-mastene i de fleste kategorier, men betydelig lavere påvirkning i 2-3 kategorier.
- I den globale oppvarmingskategorien har en 2 km-seksjon med aluminiummast et 4% lavere nettokarbonavtrykk enn seksjonen med standardstålmast. En 2 km-seksjon med M-master har en 7% lavere påvirkning enn seksjonen med standardstålmast.

Studien fremhever betydningen av bærekraftig material valg, spesielt stål og aluminium som brukes til masteproduksjon, og fordelene med resirkulering. Gjennomtenkte valg av materialer til masteproduksjon er avgjørende for å minimere miljøpåvirkningen til mastekonstruksjonen. Primærproduksjonen av stål- og aluminiumfremstilling er både materiell og energiintensiv, og en forbedret styring av naturressurser gir reelle fordeler, ikke bare for miljøet, men også for samfunnet, økonomien og menneskers helse, og reduserer behovet for primærproduksjon.

Resultatene av denne studien er nyttige for å identifisere områder der forbedring kan gjøres, og gir kunnskap for å kunne integrere klima og miljøaspekter i beslutningsprosessen. LCA kan dermed tjene som et kraftig verktøy i miljøledelsessystemer, og oppfyller de nye kravene i ISO 14001:2015-standarden som krever integrering av livssyklus-tenkning på alle stadier av en organisasjons aktiviteter; fra design- og utviklingsstadier, innkjøp, drift og vedlikehold, til slutten på livsstadiet. Dette innebærer ikke bare at sikre at oppstrøms forsyningskjeden praktiserer de samme vanene, men også at sikre bærekraftig ressursstyring ved slutten av produktets levetid.

Informasjonen i denne studien kan derfor vise seg nyttig for strategiske beslutninger hos Statnett, f.eks. designbeslutninger og anskaffelsesbeslutninger for å minimere negative miljøpåvirkninger. Resultatene gir også innsikt i fordelene med materialgjenvinning og resirkulering ved slutten av mastens livssyklus. Studien og livssyklusopplysningene gir også grunnlag for videre analyser eller sammenligninger.

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# 1 INTRODUCTION

Research and development plays an important role in Statnett's strategy to strengthen the electrical grid in an environmentally friendly way. Statnett is currently developing prototypes for two types of electric transmission towers. As part of the development phase Statnett wants to obtain knowledge on the environmental impacts associated with these new towers to support decision making processes at Statnett.

Life cycle assessment (LCA) is a methodology to assess the environmental impacts of a product encompassing the whole life cycle (cradle to grave). Hence, the environmental impacts of a product are evaluated from resource extraction to material production, product manufacturing, use of the product up to its disposal including the production wastes. The general procedure of conducting an LCA is standardised in ISO 14040 [1] and ISO 14044 [2]. In addition, a European standard EN 15804 on the sustainability of construction works has been prepared [3], as defined in ISO 14025 for Type III environmental declarations [4].

The goal of this study is to use LCA methodology to evaluate the environmental impacts of transmission towers and systems intended for 420 kV electric power transmission operated by Statnett in Norway. This assessment provides numerical results on environmental impacts for seven environmental impact categories, as required by the EN 15804 standard which is used as reference, where the contribution of each life cycle stage and different components of the system to each impact category is identified. A comparison is made between a standard Statnett steel transmission tower and two prototypes of towers currently under development.

The LCA study is done in accordance with the ISO standards 14040 and 14044 and the European standard EN 15804. Furthermore, requirements for preparation of Environmental Product Declaration (EPD) are followed [5, 6]. This way the results from the assessment can be used directly by Statnett for the preparation of an EPD if that is considered feasible.

# 2 LIFE CYCLE ASSESSMENT OF ELECTRICITY TRANSMISSION

## 2.1 Goal and scope

The goal of the study is to gain knowledge on environmental impacts of transmission towers and related activities from a life cycle perspective. The environmental impacts of two prototypes of transmission towers will be compared with Statnett's standard transmission tower. The results of the analysis can be used to support Statnett in selecting the most environmentally friendly solutions and make informed procurement requirements so that negative environmental impacts can be reduced.

The product systems to be studied include three different types of transmission towers compared in either mountainous terrain or in flat terrain:

- Aluminium tower (prototype)
- Guyed M-tower (prototype)
- Standard Statnett tower.

The towers are compared as stand-alone objects (scenarios 1a, 2a and 3) and in terms of a 2 km section of a transmission line (scenarios 1b and 2b), see Table 1 and chapter 2.3 for system boundaries.

**TABLE 1** Overview of the scenarios analysed in the LCA assessment.

| TERRAIN | TRANSMISSION TOWERS | SCENARIO | |
|---|---|---|---|
| Mountain | - Aluminium tower<br>- Standard steel tower | 1 | a Suspension tower and foundation |
| | | | b 2 km transmission line section |
| Flat | - Guyed M-tower (steel)<br>- Standard steel tower | 2 | a Suspension tower and foundation |
| | | | b 2 km transmission line section |
| | - Standard steel tower | 3 | a Two types of foundations for a suspension tower |

## 2.2 Functional unit

The product systems analysed have different functions and therefore two functional units are defined for the study:

a. Functional unit: One suspension tower including its foundations, intended for 420 kV transmission, for a given terrain (mountain or flat).
b. Functional unit: A 2 km section of a transmission line intended for 420 kV transmission, for a given terrain (mountain or flat), including one tension tower, five suspension towers, conductors, insulators and earthing and shield wires.

The service life for all scenarios is assumed to be 70 years.

## 2.3 System boundaries

The life cycle assessment for the transmission towers and transmission lines is a cradle to grave analysis. The system boundaries for all the scenarios include raw material extraction, manufacturing of components, transport of the tower, construction of the tower and transmission line, inspection and maintenance during the service life and dismantling and recycling at the end of life. For the transmission lines (scenarios 1b and 2b) the transmission losses during the use phase are also included in the calculations. The life cycle stages covered and modules in accordance with EN 15804 are shown in Table 2. A simplified diagram of transmission components within each scenario is shown in Figure 1, while a more detailed diagram of the simplified system boundaries can be seen in Figure 2, displaying which components of the transmission system belong to each life cycle stage. The life cycle inventory for each step of the life cycle is described in chapter 3.

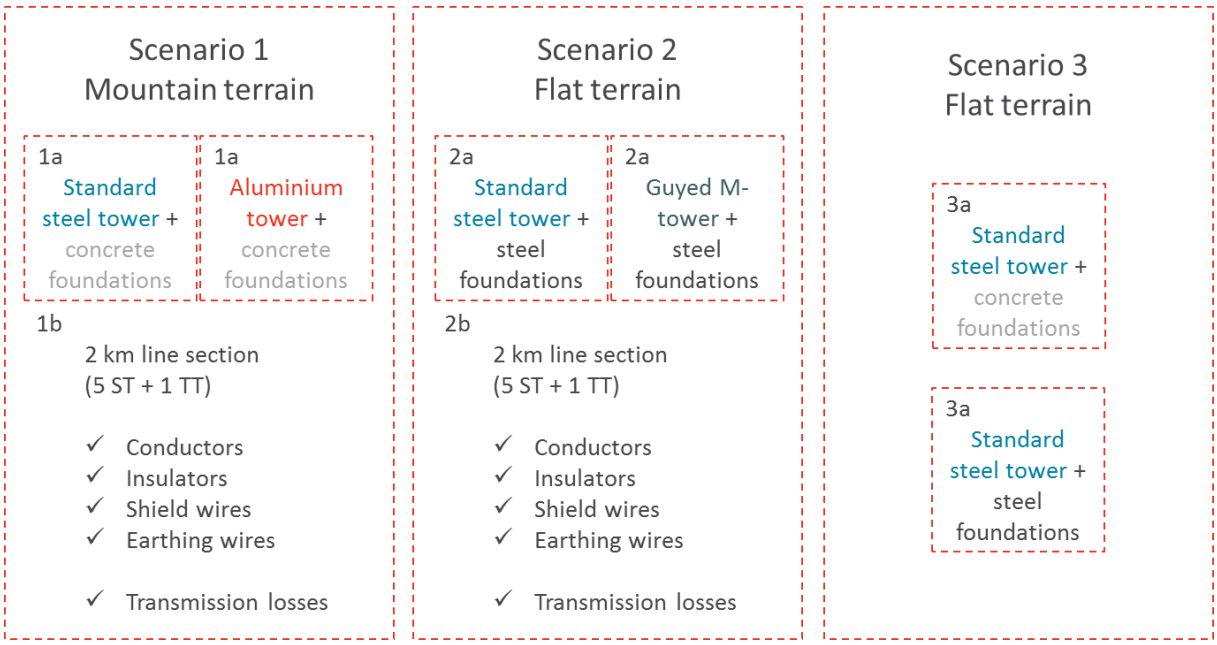



**FIGURE 1** Simplified diagram of the main transmission line components within each scenario. A more detailed definition of the study's system boundaries including all life cycle stages analysed can be seen in Table 2 and Figure 2. ST = Suspension tower, TT = Tension tower.

**TABLE 2** Life cycle stages covered in the life cycle assessment and the relevant modules in accordance with EN 15804.

| Life cycle stage | Product stage | | | Construction process stage | | Use stage | | | | | | | End of life stage | | | | Benefits and loads beyond system boundary |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | Raw materials | Transport | Manufacturing | Transport | Construction-Installation process | Use | Maintenance | Repair | Replacement | Refurbishment | Operational energy use | Operational water use | De-construction demolition | Transport | Waste processing | Disposal | Reuse, recovery, recycling potential |
| EN 15804 module | A1 | A2 | A3 | A4 | A5 | B1 | B2 | B3 | B4 | B5 | B6 | B7 | C1 | C2 | C3 | C4 | D |
| included modules in scenarios 1a, 2a and 3a | x | x | x | x | x | | x | | | | | | x | x | | x | x |
| Included modules in scenarios 2a and 2b | x | x | x | x | x | x | x | | | | | | x | x | | x | x |

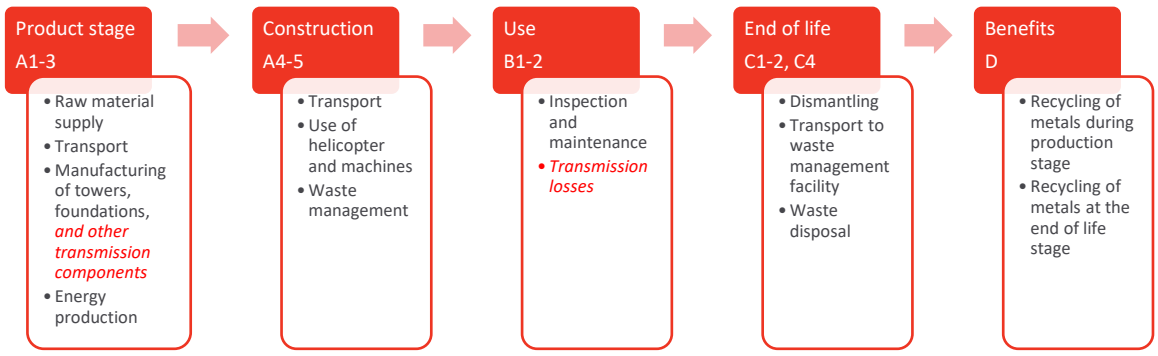



**FIGURE 2** Simplified system boundaries for the life cycle assessment of transmission towers and transmission lines, identifying each life cycle stage as defined in EN 15804 . Parts shown in italic red are specific for the 2 km transmission scenarios (1b and 2b).

### 2.3.1 Scenario 1: Aluminium and Standard towers in mountain terrain (1a & 1b)

Two comparative assessments are done for Aluminium and Standard steel towers in mountainous terrain. Scenario 1a is a comparison of the two different transmission towers in mountainous terrain including their foundations. Scenario 1b is a comparison of a 2-km section of a transmission line using either the Standard steel tower or the Aluminium tower. The parts of the transmission system included in scenario 1a and 1b are listed in Table 3.

**TABLE 3** Overview of what is included within the system boundaries for scenario 1a - transmission tower and scenario 1b – 2 km transmission line.

| | | TRANSMISSION TOWER SCENARIO 1A | | TRANSMISSION LINE SCENARIO 1B | |
|---|---|---|---|---|---|
| | | Standard tower | Aluminium tower | Standard tower | Aluminium tower |
| Terrain | Mountain | x | x | x | x |
| | Flat | | | | |
| Transmission tower | Suspension tower | 1 | 1 | 5 | 5 |
| | Tension tower (Standard steel) | 0 | 0 | 1 | 1 |
| Foundations | in-situ concrete | x | x | x | x |
| | Prefabricated steel | | | | |
| Transmission components | Insulators | | | x | x |
| | Earthing wire | | | x | x |
| | Shield wire | | | x | x |
| | Conductor | | | x | x |
| Construction | Transport and use of machinery | x | x | x | x |
| O&M | Transmission losses | | | x | x |
| | Maintenance | x | x | x | x |
| End of Life | Dismantling and recycling | x | x | x | x |

### 2.3.2 Scenario 2: Guyed M-towers and Standard towers in flat terrain (2a & 2b)

Two comparative assessment are done for guyed M-towers and Standard steel towers in flat terrain. Scenario 2a is a comparison of the two types of transmission towers in flat terrain including their foundations. The scenario is then expanded to include the necessary components of a 2 km section of a transmission line (scenario 2b). The parts of the transmission system included in scenario 2a and 2b is shown in Table 4.

**TABLE 4** Overview of what is included within the system boundaries for scenario 2a - transmission tower and scenario 2b – 2 km transmission line.

| | | TRANSMISSION TOWER SCENARIO 2A | | TRANSMISSION LINE SCENARIO 2B | |
|---|---|---|---|---|---|
| | | Standard tower | Guyed M-tower | Standard tower | Guyed M-tower |
| Terrain | Mountain | | | | |
| | Flat | x | x | x | x |
| Transmission tower | Suspension tower | 1 | 1 | 5 | 5 |
| | Tension tower (Standard steel) | 0 | 0 | 1 | 1 |
| Foundations | in-situ concrete | | | | |
| | Prefabricated steel | x | x | x | x |
| Transmission components | Insulators | | | x | x |
| | Earthing wire | | | x | x |
| | Shield wire | | | x | x |
| | Conductor | | | x | x |
| Construction | Transport and use of machinery | x | x | x | x |
| O&M | Transmission losses | | | x | x |
| | Maintenance | x | x | x | x |
| End of Life | Dismantling and recycling | x | x | x | x |

### 2.3.3 Scenario 3: Foundations in flat terrain (3a)

In scenario 3a two different types of foundations for the Standard steel transmission tower are compared in flat terrain:

- Standard Statnett transmission tower with **in-situ concrete foundations**
- Standard Statnett transmission tower with **prefabricated steel foundations**

The parts of the transmission system included in scenario 3a is shown in Table 5.

**TABLE 5** Overview of what is included within the system boundaries for scenario 3a.

| | | TRANSMISSION TOWER SCENARIO 3A | |
|---|---|---|---|
| | | Standard Statnett | Standard Statnett |
| Terrain | Mountain | | |
| | Flat | x | x |
| Transmission tower | Suspension tower | 1 | 1 |
| | Tension tower (Standard steel) | 0 | 0 |
| Foundations | in-situ concrete | x | |
| | Prefabricated steel | | x |
| Transmission components | Insulators | | |
| | Earthing wire | | |
| | Shield wire | | |
| | Conductor | | |
| Construction | Transport and use of machinery | x | x |
| O&M | Transmission losses | | |
| | Maintenance | x | x |
| End of Life | Dismantling and recycling | x | x |

## 2.4 Environmental impact categories

In accordance with the requirements of EN 15804, the following environmental impact categories are used to present results in the Life Cycle Impact Assessment (LCIA) in chapter 4:

- Global warming
- Ozone depletion
- Acidification
- Eutrophication
- Photochemical ozone creation
- Depletion of abiotic resources (elements)
- Depletion of abiotic resources (fossil)

More information on these categories can be found in Appendix 1. The environmental impact assessment methodology used is CML 2001 (Version January 2016).

# 3 LIFE CYCLE INVENTORY

The data collection procedures for the assessment are described below. Data was collected for the manufacturing of transmission towers, foundations, conductors, shield and earthing wires and insulators. Moreover, information on transports and construction practices were collected as well as data on yearly operation and the end of life scenario. The system is modelled in the GaBi LCA software from thinkstep using GaBi databases.

## 3.1 Transmission towers

For all tower types, the following assumptions were made:

- Load class: Middle
- Average tower height
- Wind load: 44 m/s, 500 years return period
- Span length: ca 400 m
- Ice load: 6 kg/m, 150 year return period
- Shield wire: Gondul
- Phase conductor: Triplex Grackle in mountain terrain, Duplex Parrot in flat terrain

### 3.1.1 Standard steel towers

Information on electricity and material use for the manufacturing and surface treatment, i.e. galvanisation, of steel towers was based on data obtained from three manufacturers of steel towers. Background data on average European steel production and German zinc production was used in the assessment [7]. For the manufacturing of towers, average European mixes were used for energy inputs such as electricity, natural gas and fossil fuels.

Total weights for Standard towers is based on experience, see Table 6. An example of a Standard steel tower can be seen in Figure 3.

**TABLE 6** Total weights per tower used in this study for Standard towers. Weights include guy wires and attachments.

| TERRAIN | SUSPENSION TOWER [TONNES] | TENSION TOWER [TONNES] | CONDUCTORS PER PHASE |
|---|---|---|---|
| Mountain | 11.0 | 22.0 | Triplex Grackle |
| Flat | 10.3 | 22.0 | Duplex Parrot |

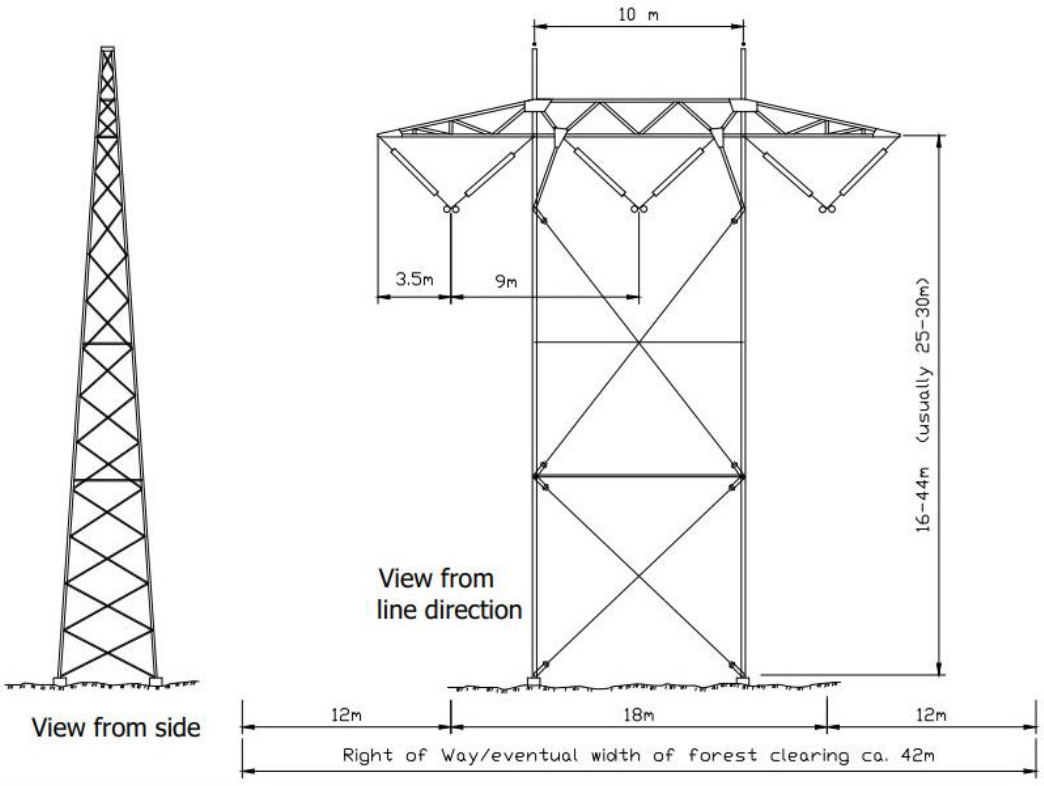



**FIGURE 3** Statnett's Standard suspension tower for 420 kV transmission.

### 3.1.2 Guyed M-towers

The same information on steel tower manufacturing was used for the M towers as described for the Standard tower above.

Total weights for M-towers were obtained from Statnett (Table 7) and are based on the prototype currently in development (Figure 4). For each M-tower, there are 2 guyed anchors. In this study, it is assumed that no anchor plates are needed for the construction, only rock anchors and anchor rods.

**TABLE 7** Total tower weights used in this study for M-towers. Weights include guy wires and anchors.

| TERRAIN | SUSPENSION TOWER [TONNES] | CONDUCTORS PER PHASE |
|---|---|---|
| Flat | 7.3 | Duplex Parrot |

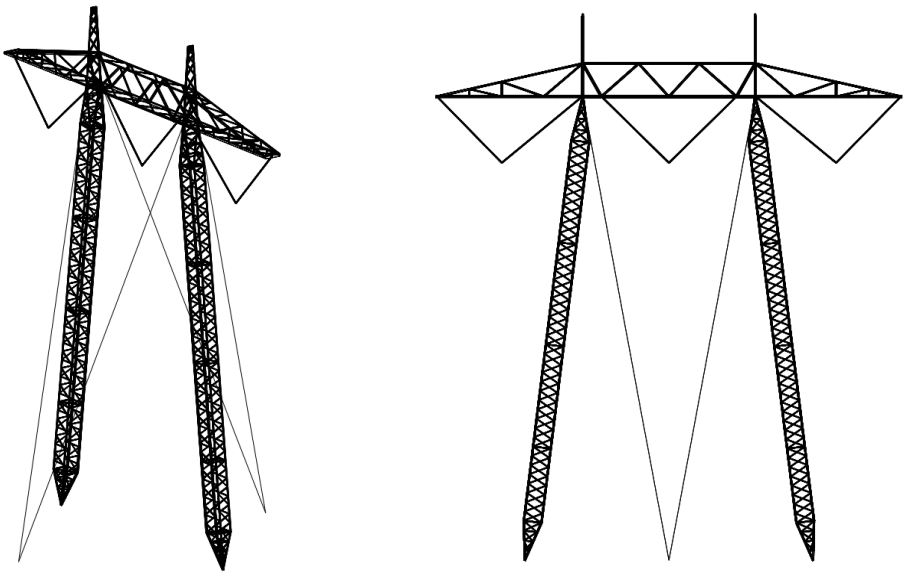


**FIGURE 4** Side and front model view of Statnett's guyed M-tower (suspension tower).

### 3.1.3 Aluminium towers

Background data for the production of average European aluminium ingot was used for the assessment [7]. The aluminium ingot was used for the manufacturing of aluminium profiles and plates, where information on electricity and material use was obtained from two manufacturers in Norway. A European electricity grid mix was used for electricity inputs for the manufacturing of profiles and plates.

Aluminium tower weights are based on the prototype currently in development (Figure 5). Total weights for Aluminium towers were based on prototype design and manufacturing and can be seen in Table 8.

**TABLE 8** Total tower weights used for Aluminium-towers, including bolts, guy wires and attachments.

| TERRAIN | SUSPENSION TOWER [TONNES] | CONDUCTORS PER PHASE |
|---|---|---|
| Mountain | 5.0 | Triplex Grackle |

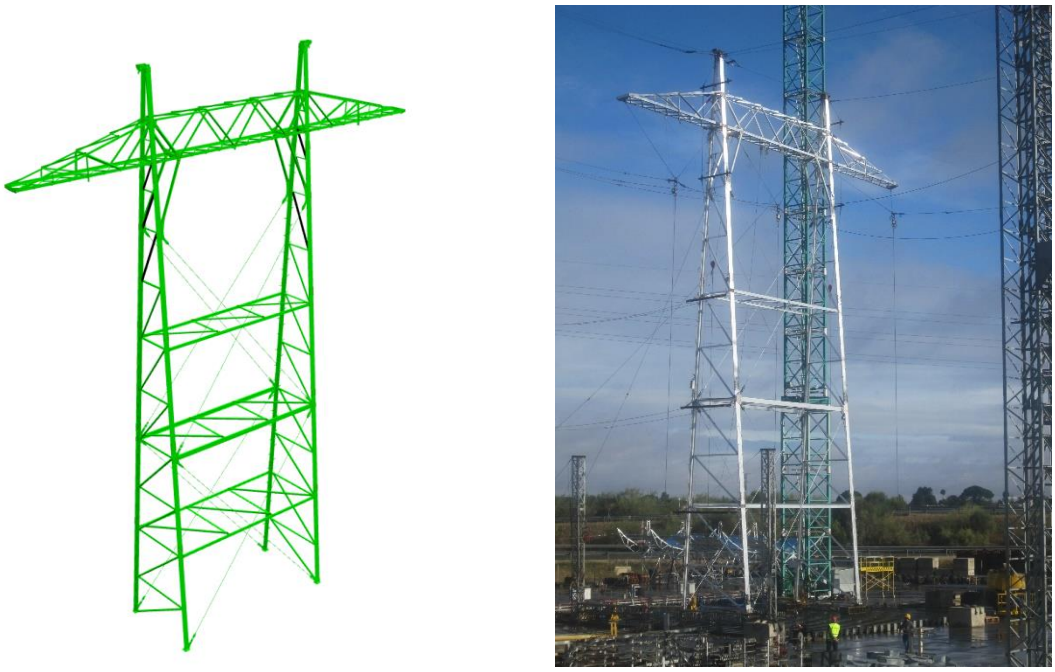


**FIGURE 5** Aluminium tower design (left) and photo (right) during construction phase. Photo: EFLA, Nov 2017.

## 3.2 Foundations

### 3.2.1 Concrete foundations

Background data on European ready-mix concrete (C30/37), reinforced steel and galvanized steel was used in the model [7].

Concrete foundation weights, used in this study for Standard towers and aluminium towers, is based on typical Statnett foundations and can be seen in Table 9 and in Figure 6.

**TABLE 9** Assumed weights for standard concrete foundations for Standard towers (mountainous and flat terrain) and Aluminium towers (mountainous terrain). All weights are given per tower, assuming four foundations per tower.

| | | REINFORCEMENT STEEL [KG PER TOWER] | CONCRETE [KG PER TOWER] | BOLTS [KG PER TOWER] |
|---|---|---|---|---|
| Suspension tower | Mountain terrain | 160 | 3,840 | 133 |
| | Flat terrain | 850 | 20,400 | 89 |
| Tension tower | Mountain terrain | 480 | 11,520 | 333 |
| | Flat terrain | 4,000 | 96,000 | 222 |

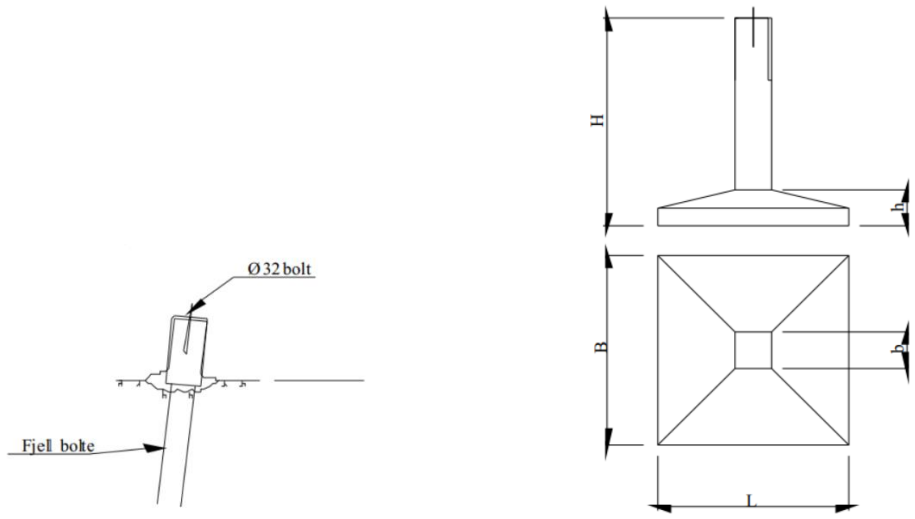



**FIGURE 6** Typical concrete foundations for mountain terrain (left) and flat terrain (right) [8].

### 3.2.2 Prefabricated steel foundations

Two types of prefabricated steel foundations are used in this project; one type for the Standard tower and another type for the guyed M-tower. Background data on average European steel (EU-27) and German zinc production is used for the manufacturing of structural steel in prefabrifacted steel foundations [7]. Galvanization is assumed 4% of total foundation weight.

### 3.2.2.1 Standard tower steel foundations

Information on steel foundations for Standard towers is based on experience from the Balsfjord-Skaidi project in Norway [9], where steel foundations were used and transported via winter trails. The project was used to classify steel foundations into three strength classes (1-3), see Table 10 for corresponding foundation weights. The foundations are divided into three main sections which are bolted together; bottom plate, L and H profiles, column and adapter, see Figure 7.

**TABLE 10** Prefabricated steel foundations for Standard suspension and tension towers, including galvanisation. Weights are given per foundation, assuming 4 foundations per Standard tower.

| CATEGORY | STRENGTH CLASS 1 [TONNES PER FOUNDATION] | STRENGTH CLASS 3 [TONNES PER FOUNDATION] |
|---|---|---|
| Flat terrain | Suspension Towers | Tension Towers |
| Total weight | **2.1** | **5.1** |

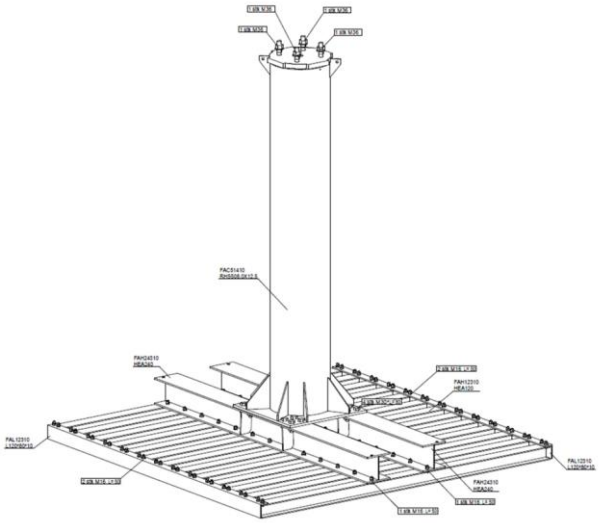


**FIGURE 7** Prefabricated steel foundations for Standard steel towers, strength class no. 1. Source: Hallgrim Berg, Statnett SF 2016.

### 3.2.2.2 M-tower steel foundations

Information on steel foundations for M-towers was obtained from Statnett. For each M-tower there are 2 compression foundations. See Table 11 for corresponding foundation weight.

**TABLE 11** Prefabricated steel foundations for M-towers, including galvanisation. Weights are given per foundation, assuming 2 foundations per M-tower.

| FLAT TERRAIN | SUSPENSION M-TOWERS [TONNES PER FOUNDATION] |
|---|---|
| Total weight | **1.4** |

## 3.3 Conductors, shield wire, earthing wire and insulators

Key figures in material use for conductors, shield wire, earthing wire and insulators per km transmission can be seen in table 12. Information is based on data from manufacturers and includes material use only, not energy use during manufacturing of components. For conductors, insulators and shield wire, the same amount of materials are used for all tower types (Standard, M-tower, Aluminium), but for earthing wires the amount depends on terrain and number of foundations. Transport of conductors, insulators, shield and earthing wires, from manufacturer to building site is not included in this study, as these components are added mainly for reference.

**TABLE 12** Key figures in material use for three-phase transmission components within a 2 km section, assuming 6 towers per 2 km. All amounts are in kg per 2 km section.

| TRANSMISSION COMPONENT | TYPE | STEEL [KG ] | ALUMINIUM [KG] | COPPER [KG] | GLASS [KG] | CAST IRON [KG] |
|---|---|---|---|---|---|---|
| Conductors | Duplex Parrot | 9,100 | 25,400 | | | |
| | Triplex Grackle | 10,800 | 28,400 | | | |
| Insulators | | 1,500 | 500 | | 2,100 | 1,700 |
| Shield wire | | 3,200 | 1,100 | | | |
| Earthing wire | | | | 126 (mount. t.)<br>246 (flat t., Standard)<br>146 (flat t., M-tower) | | |

**FIGURE 8** View from the top of a Standard transmission tower in Nedre Røssåga-Namsskogan, carrying conductors, insulators and two shield wires.

## 3.4 Transport and construction

### 3.4.1 Transport of towers and foundations

Average oceanic transport distances were obtained from manufacturers, i.e. transport from factory to warehouse in Norway, see table 13. For simplification and for comparison, the same transport distance from tower manufacturer to warehouse in Norway was used for all tower types; Standard, Aluminium and M-tower. Background data on different transport modes was used in the study [7].

**TABLE 13** Average transport distances assumed for the oceanic transport of towers, from manufacturer to warehouse in Norway. Numbers are average transport distances based on information from three manufacturers of steel towers (in Turkey, Croatia and Finland).

| TRANSPORT | MODE OF TRANSPORT | DISTANCE [KM] |
|---|---|---|
| From manufacturer to port | Truck-trailer | 266 |
| Ocean shipping to Norway | Cargo ship | 5297 |
| From port in Norway to warehouse | Truck-trailer | 120 |

### 3.4.2 Use of machinery

Information on machinery use during construction of towers and foundations was obtained from EFLA, i.e. estimated based on experience, see table 14. The same use of machinery was assumed for different tower types in mountain terrain, and for different tower types in flat terrain.

**TABLE 14** Assumptions on use of machinery during construction of towers and their foundations in mountainous and flat terrain.

| TERRAIN | MACHINE TYPE | USE OF MACHINERY PER TOWER [HOURS] | ESTIMATED FUEL USE [L/HOUR] |
|---|---|---|---|
| Mountain terrain | Excavator | 16 | 10 |
| | Compressor | 15 | 5 |
| Flat terrain | Excavator | 40 | 15 |
| | Crane machine | 8 | 15 |

### 3.4.3 Transport between loading site and construction site

Helicopter transport is assumed for the transport of all materials in mountain terrain, and for the transport of Standard towers and concrete foundations in flat terrain. A single engine turboshaft powered helicopter is assumed (e.g. Eurocopter AS350 B3). According to the civil aviation emission inventory of Switzerland, the helicopter uses 152 kg fuel per hour (hourly emissions) or 27.5 kg fuel per LTO (landing/take-off) cycle [10].

Tracked vehicles are assumed for the transport of Standard steel foundations in flat terrain, and the transport of M-towers and their steel foundations.

Assumptions made for transport between loading site and construction site can be seen in Table 15.

**TABLE 15** Assumptions for transport of towers and foundations between loading site and construction site. All return trips assume empty returns.

| TYPE OF CARRIER | TRANSPORT CAPACITY | MAXIMUM LOAD PER TRIP | ESTIMATED LOAD PER TRIP | ESTIMATED FUEL CONSUMPTION |
|---|---|---|---|---|
| Tracked articulated all-terrain carrier | 4 km/hour | 10 tonnes | 10 tonnes | 30 L per hour |
| Single engine helicopter | 15 min roundtrip | 1.1 tonnes | 0.9 tonnes | 152 kg (185 L) per hour |

## 3.5 Operation

### 3.5.1 Maintenance and inspection

Information on maintenance and inspection throughout a 70 year lifetime was obtained from Statnett and is based on experience, see Table 16). Average transport capacity and fuel consumption numbers are used to estimate total fuel use of 6 wheeled all-terrain vehicles (ATVs, e.g. Can-Am Outlander) and snowmobiles (e.g. Arctic Cat, Polaris), see Table 17.

**TABLE 16** Inspection and controls during a 70 year lifetime of transmission system.

| TYPE OF INSPECTION | DURATION | INTERVAL | MODE OF TRANSPORT |
|---|---|---|---|
| Ground inspection | 1 hr/km | Yearly | Summer: 6x6 ATV<br>Winter: Snowmobile |
| Forest inspection | 6 min/km | Every 5 years | Helicopter |
| Heat inspection | 1 hr/km | Yearly | Summer: 6x6 ATV<br>Winter: Snowmobile |
| Air inspection | 7.5 hrs/km | Every 7.5 years | Summer: 6x6 ATV<br>Winter: Snowmobile |
| Air control | 10.5 hrs/km | Every 10 years | Summer: 6x6 ATV<br>Winter: Snowmobile |
| 60 year control | 22.5 hrs/km | Every 60 years | Summer: 6x6 ATV<br>Winter: Snowmobile |

**TABLE 17** Estimated fuel consumption and transport capacity of inspection vehicles.

| TRANSPORT MODE | ASSUMED FUEL CONSUMPTION | AVERAGE MILEAGE |
|---|---|---|
| 6x6 ATV | 10 L/100 km | 18 km/hr |
| Snowmobile | 20 L/100 km | 45 km/hr |
| Helicopter | 152 kg (185 L) per hour | - |

### 3.5.2 Transmission losses

Information on average transmission losses for the 420 kV transmission system in the year 2016 was obtained from Statnett. A weighted average of transmission losses from four 420 kV transmission lines in Statnett's transmission system was used for this study, i.e. 174 MWh/km/year over 70 years, see table 18.

**TABLE 18** Estimated yearly transmission losses, based on transmission losses for four 420 kV lines in Statnett's transmission system in the year 2016.

| TRANSMISSION LINE (420 KV) | TRANSMISSION LOSSES PER LINE [MWH/KM/YR] | TRANSMISSION LENGTH [KM] | TOTAL TRANSMISSION LOSSES [MWH/YR] |
|---|---|---|---|
| Klæbu-Viklandet | 130 | 131 | 17,026 |
| Arendal-Bamle | 211 | 73 | 15,303 |
| Sylling-Tegneby | 499 | 48 | 23,728 |
| Salten-Svartisen | 73 | 124 | 9,040 |
| | **Total** | 375 | 65,096 |
| | **Total transmission losses, weighted average [MWh/km/yr]** | | **174** |

## 3.6 End of Life

At the end of the designated service time of 70 years, the towers are dismantled and transported to professional waste management services, where materials are either recycled, reused or disposed of in another way e.g. through landfilling or incineration.

### 3.6.1 Dismantling

For scenarios 1 and 2, Statnett estimates that 20% of total fuel consumption during the construction period is needed during the dismantling, see chapter 3.4. Towers are removed and the top layer of all concrete foundations, leaving materials in the ground >0,2 m below the surface. Prefabricated steel foundations are left in the ground.

In scenario 3a, where different foundation types are compared for the Standard steel tower, results are presented either 1) leaving the steel foundations in the ground, using 20% of total fuel consumption during construction, or 2) retrieving steel foundations and recycling the material, using 80% of the total fuel consumption during construction.

In mountain terrain, all removed materials are transported 4 km via helicopter to a disassembly ground. In flat terrain, disassembled Standard towers are transported 4 km via helicopter while M-towers are transported via tracked articulated all-terrain carrier.

In scenarios 1b and 2b, for the dismantling of conductors, insulators, shield and earthing wires, it is assumed that an additional 20% of total fuel consumption during the construction period is needed to draw out conductors and wires, and remove insulators and earthing wires.

### 3.6.2 Disposal

For simplification, it is assumed in this study that all distmantled materials and components are removed and delivered from the disassembly ground to recognised waste management services, a total distance of 50 km via truck-trailer. Further transport is not included in the study.

For recyclable materials, an avoided burden is calculated, i.e. a positive impact or “credit” due to the potential use for recycled materials in another product system. A list of assumptions made for the calculations of avoided burden can be seen in Table 19. Market-based price ratios are used for the calculation of avoided burden of aluminium scrap and steel scrap [11, 7]. Due to the integrity and purity of the aluminium tower structure, a higher ratio of avoided burden was chosen for the recycling of its aluminium content than for other aluminium scrap. As no market-based recycling ratios were available in the GaBi database for copper, a literature-based recycling processing rate is used in this study [12].

The final disposal of other inert materials such as insulator glass and concrete, have not been included in this study.

**TABLE 19** Assumptions used for the calculation of avoided burden for recyclable materials within the study.

| TRANSMISSION UNIT | MATERIAL | AMOUNT OF USED MATERIAL TO RECYCLING | AVOIDED BURDEN |
|---|---|---|---|
| Towers | Aluminium | 100% | 89% [11, 7] |
| | Steel | 100% | 47% [11, 7] |
| Foundations | Steel | 100% | 47% [11, 7] |
| Conductors | Aluminium | 100% | 58% [11, 7] |
| | Steel | 100% | 47% [11, 7] |
| Insulators and fittings | Aluminium | 100% | 58% [11, 7] |
| | Steel and cast iron | 100% | 47% [11, 7] |
| Shield wire | Aluminium | 100% | 58% [11, 7] |
| | Steel | 100% | 47% [11, 7] |
| Earthing wire | Copper | 100% | 70% [12] |

# 4 LIFE CYCLE IMPACT ASSESSMENT

## 4.1 Scenario 1: Two tower types in mountain terrain

This chapter presents results for Scenario 1, i.e. for two different transmission towers, Standard steel and Aluminium, in mountainous terrain, including foundations.

### 4.1.1 Scenario 1a: Standard steel and Aluminium towers

The relative contribution of the different life cycle stages of the Standard steel and Aluminium towers, including foundations, can be seen in Figures 9 and 10. The two tower types are compared in Figures 11 and 12.

In four out of seven impact categories, raw material extraction and manufacturing of Standard steel towers and foundations account for at least half of the total impacts during the entire life cycle (Figure 9), i.e. for global warming, ozone depletion, photochemical creation and abiotic depletion (fossil) impact categories. This is due to an energy and material intensive production process of steel. Fuel use during construction (A4-A5) is also an important factor in most impact categories. The galvanization process is dominant in one environmental impact category, Abiotic Depletion (elements), which is due to the mining and use of zinc. By recycling the tower steel at the end of life, virgin steel production is averted in another system and is here calculated as a benefit to the results, decreasing the impact in six out of seven categories.

For the Aluminium tower, the material processing and manufacturing of aluminium profiles used within the tower is dominant in all categories (Figure 10). This is due to the energy intensive alumina production, and electrolysis unit processes during the primary aluminium production. In the Abiotic Depletion (elements) category, which is an indicator of the depletion of non-renewable resources, the use of galvanized screws used for the foundations also weighs heavily. The recycling of aluminium scrap from the tower leads to significant benefits in all impact categories, decreasing the total impact.

**FIGURE 9** Results for Scenario 1a, **Standard steel tower** with concrete foundations in mountain terrain. The relative scale (100%) shows the contribution of different components to different impact categories.

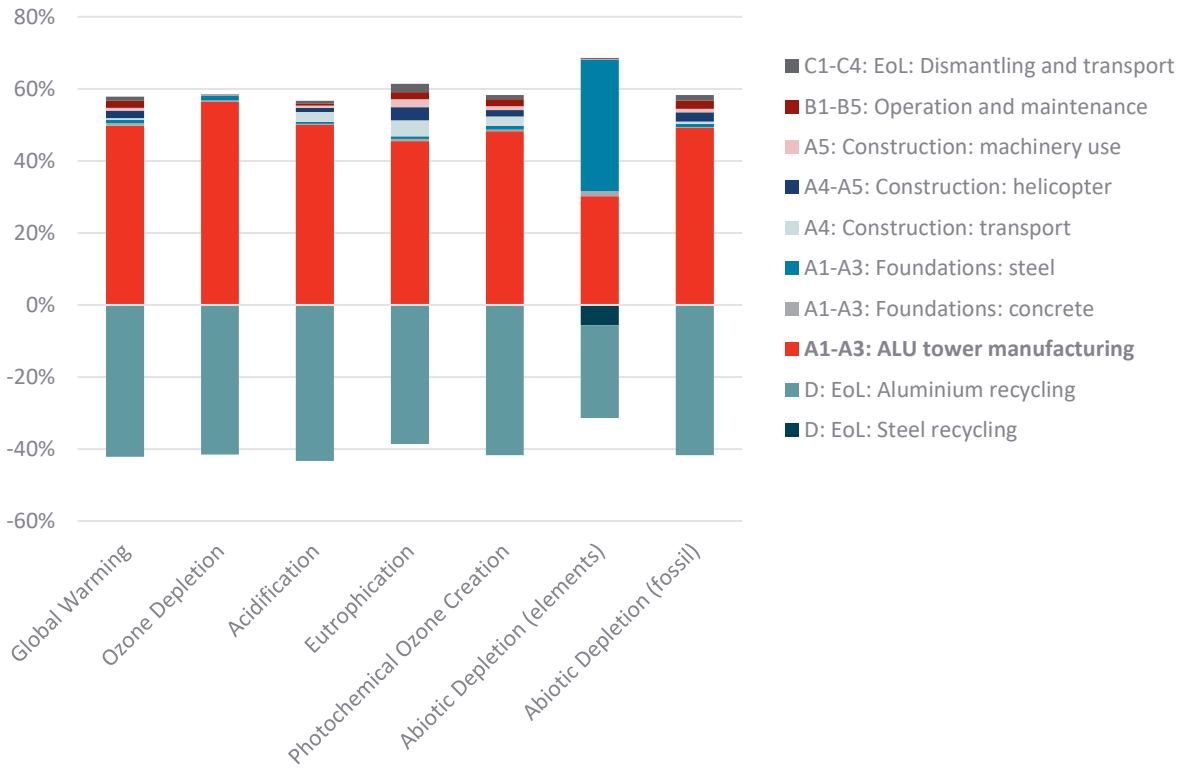
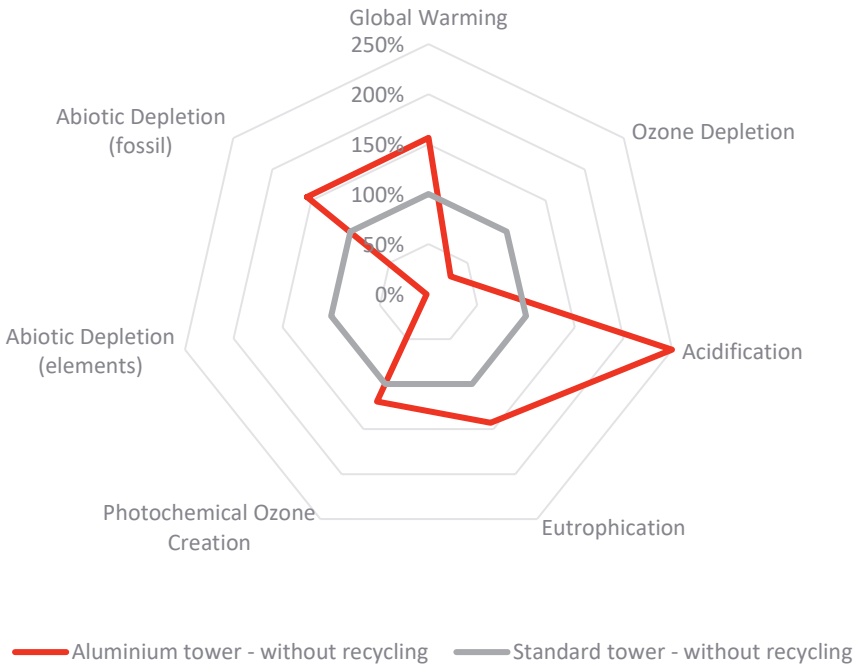



**FIGURE 10** Results for Scenario 1a, **Aluminium tower** with concrete foundations in mountain terrain. The relative scale (100%) shows the contribution of different components to different impact categories.



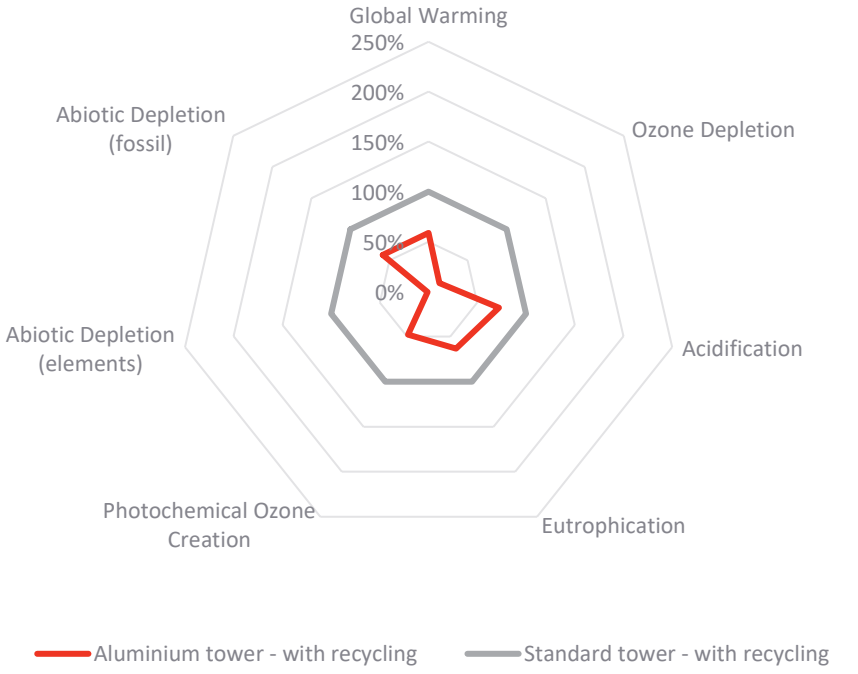




**FIGURE 11** Results for Scenario 1a, Aluminium tower as % of Standard steel tower (set to 100%), both with concrete foundations in mountain terrain. The figure above shows the gross results for both towers, not including the calculated avoided burden due to recycling at the end of life, while the figure below (net results) includes the recycling, thus demonstrating its importance.

In Figure 11, the results of the two tower types are compared within all seven impact categories, with (net) and without (gross) the benefits of recycling. As can be seen from Figures 9 and 10 and is evident from Figure 11, the recycling of materials and the resulting avoided burden can significantly lower the impacts within each category. This avoided burden is significant in the case of Aluminium recycling. When recycling is accounted for, the net impacts of the Aluminium tower is lower than the net impacts of the Standard steel tower in all impact categories.

In Figure 12, the carbon footprints, i.e. the global warming impact, of the two tower types are compared from a life cycle perspective. If gross impacts are considered, i.e. without recycling, it is observed that the total impact of Aluminium tower is more than 50% higher than the impact of the Standard steel tower. However, when recycling has been taken into account, the net impact of the Aluminium tower is 43% lower than the impact of the Standard steel tower.

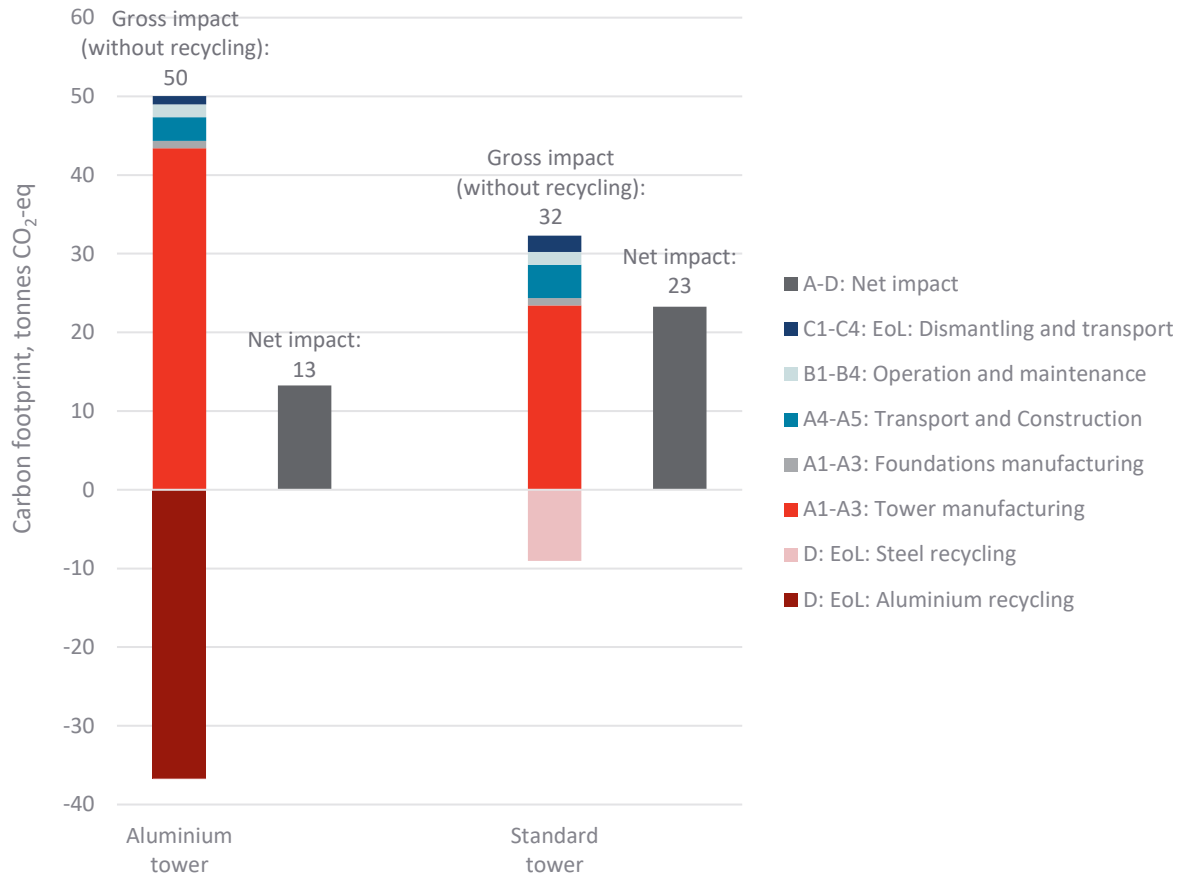



**FIGURE 12** Results for Scenario 1a, carbon footprint of the Standard steel tower and the Aluminium tower.

### 4.1.2 Scenario 1b: 2 km transmission with Standard steel and Aluminium towers

The same life cycle assessment was performed for Aluminium towers and Standard steel towers in mountainous terrain for a 2-km transmission section, this time including conductors, insulators, shield and earthing wires. The results include transmission losses during a 70-year lifetime. Results for each tower type are presented in Figures 13 and 14, and compared in figures 15 to 17.

When looking at results from the 2-km section for the Standard steel towers (Figure 13), it is observed that the environmental impacts of the conductors and transmission losses are heavier than those of the towers in five out of eight impact categories. The conductors are mostly composed of aluminium, which has an energy intensive production process. Transmission losses dominate in three categories, i.e. global warming, eutrophication and abiotic depletion (fossil). This is due to additional electricity production to account for transmission losses in the Norwegian electricity grid mix.

The above observations are identical for a 2-km section of Aluminium towers (Figure 14). When other components have been added to the transmission section, the conductors and transmission losses become dominant in five out of seven impact categories. The recycling of steel, copper and aluminium (Figures 13 and 14), from towers, conductors and earthing wires, becomes a significant factor in all impact categories for avoided burdens. When comparing net results of the 2-km sections of Aluminium and Standard towers, including recycling, the aluminium towers have similar or lower impacts in all seven impact categories, see Figure 15.

In the global warming category, a 2-km section with Aluminium towers has a similar or a 4% lower net carbon footprint than an equivalent section of Standard steel towers (Figure 16). For a 2-km transmission section of both tower types, transmission losses account for 57-61% of the gross carbon footprint or 72-75% of the net carbon footprint. If transmission losses were not included, the diffierence between the two tower would become significant (>10%), i.e. a 2-km section of Aluminium towers would have a 15% lower net carbon footprint than Standard steel towers (Figure 17).

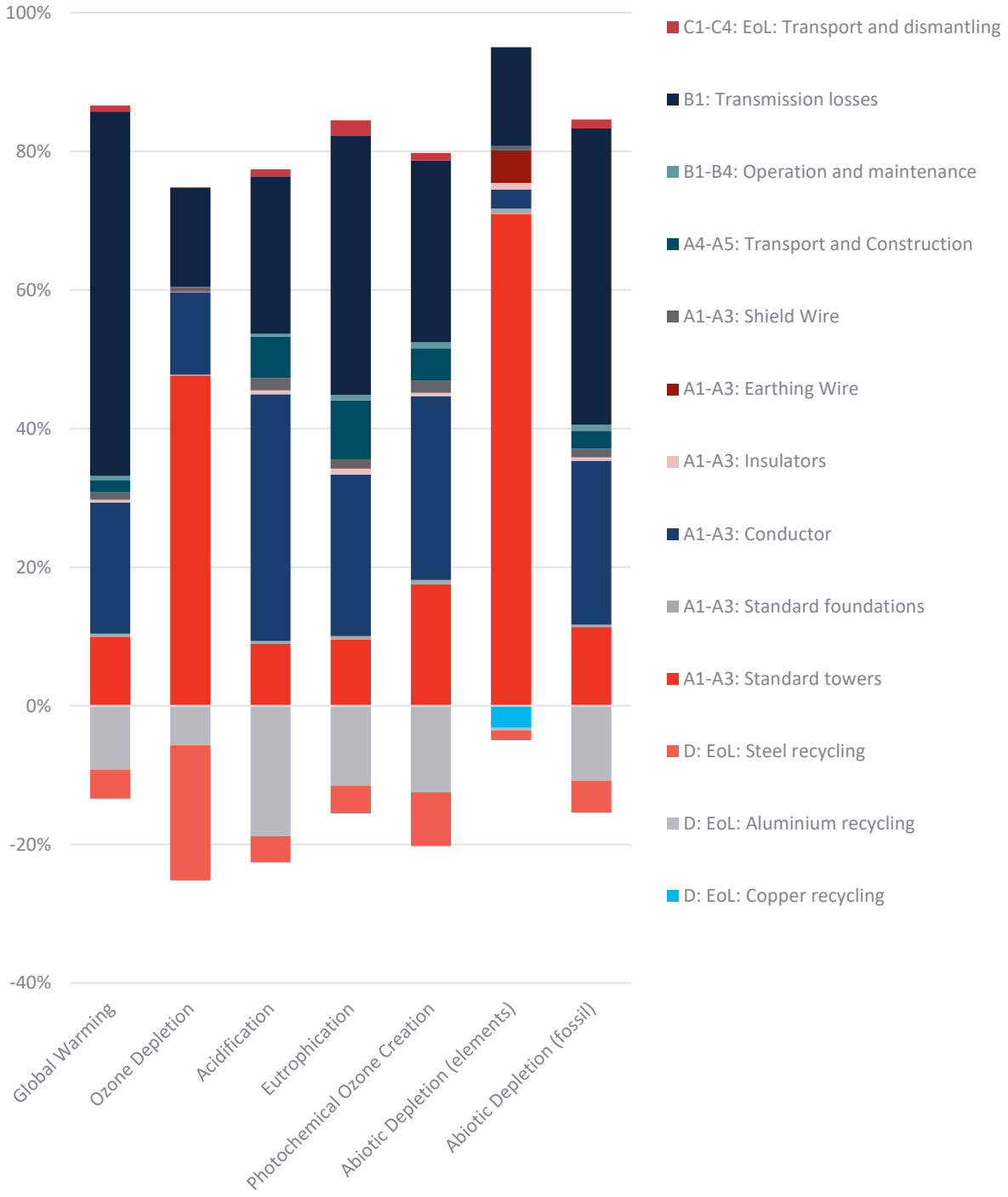



**FIGURE 13** Results for Scenario 1b, a 2-km line section of **Standard steel towers** with concrete foundations in mountain terrain. The line section includes five suspension towers and one tension tower, all Standard steel towers. The relative scale (100%) shows the contribution of different components to different impact categories.

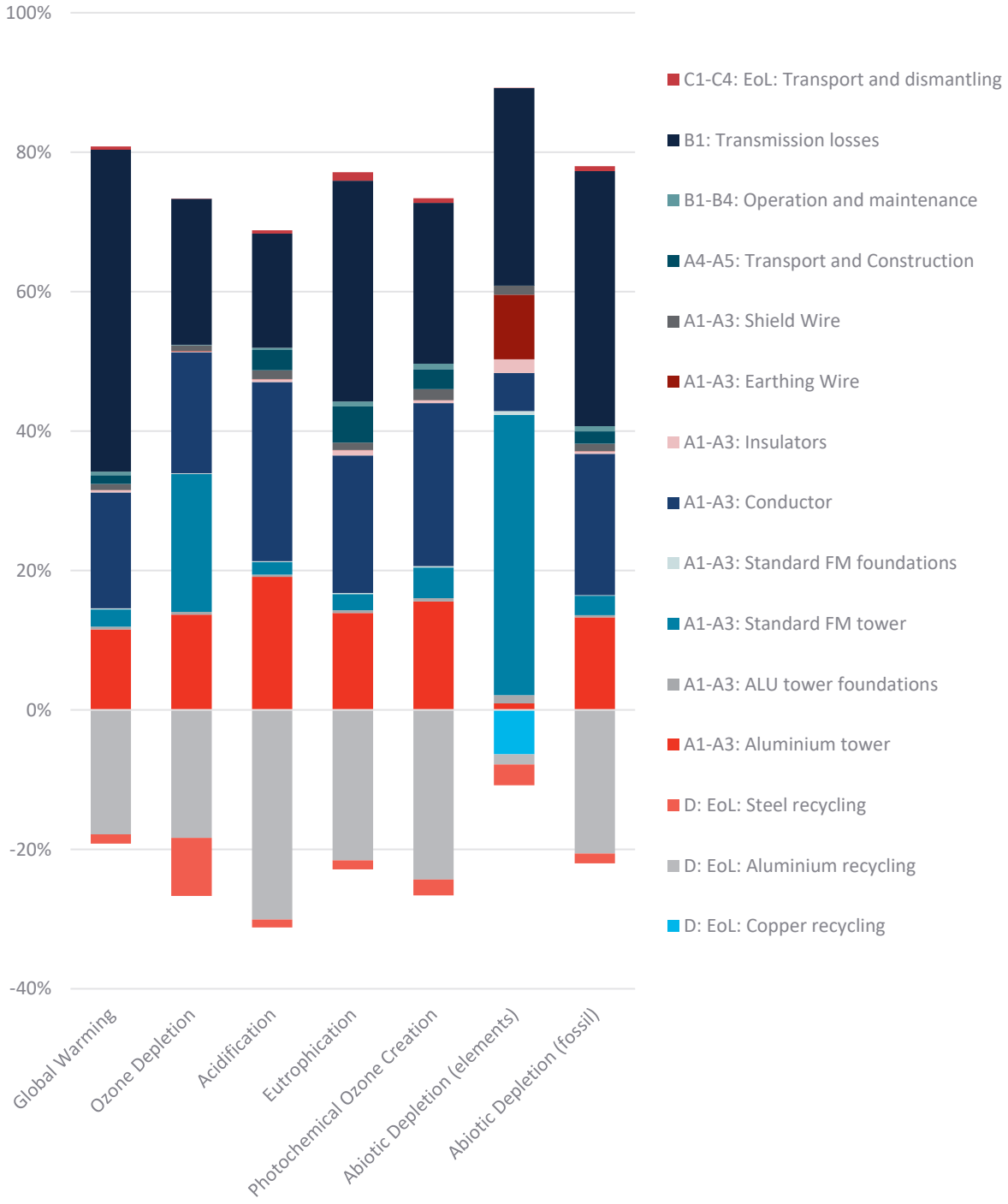
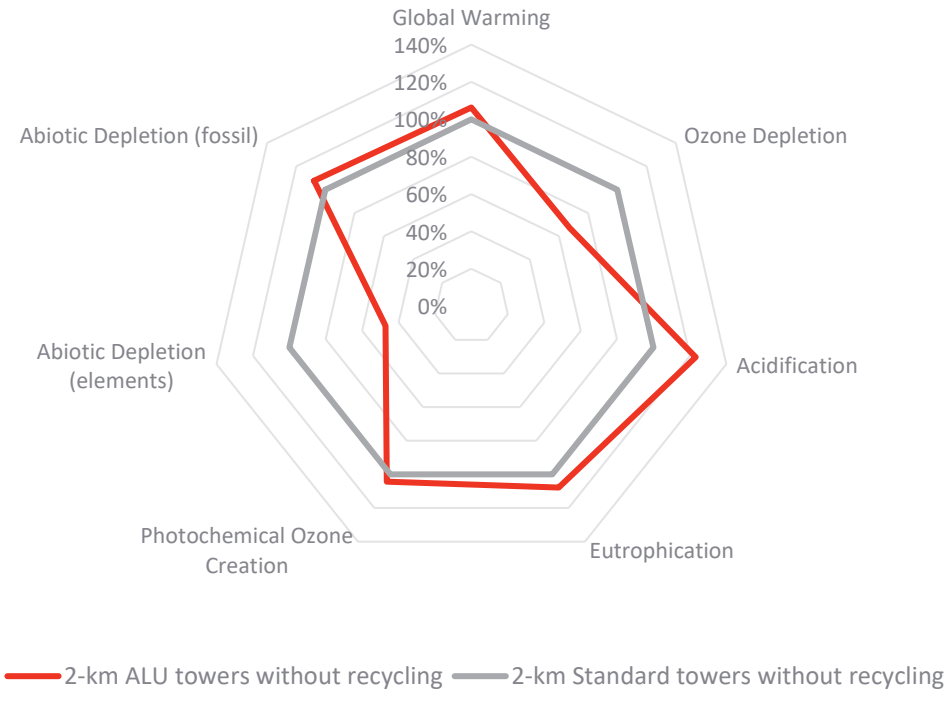



**FIGURE 14** Results for Scenario 1b, a 2-km line section of **Aluminium towers** with concrete foundations in mountain terrain including the transmission losses. The line section includes five suspension towers, Aluminium towers, and one tension tower, which is a Standard steel tower. The relative scale (100%) shows the contribution of different components to different impact categories.



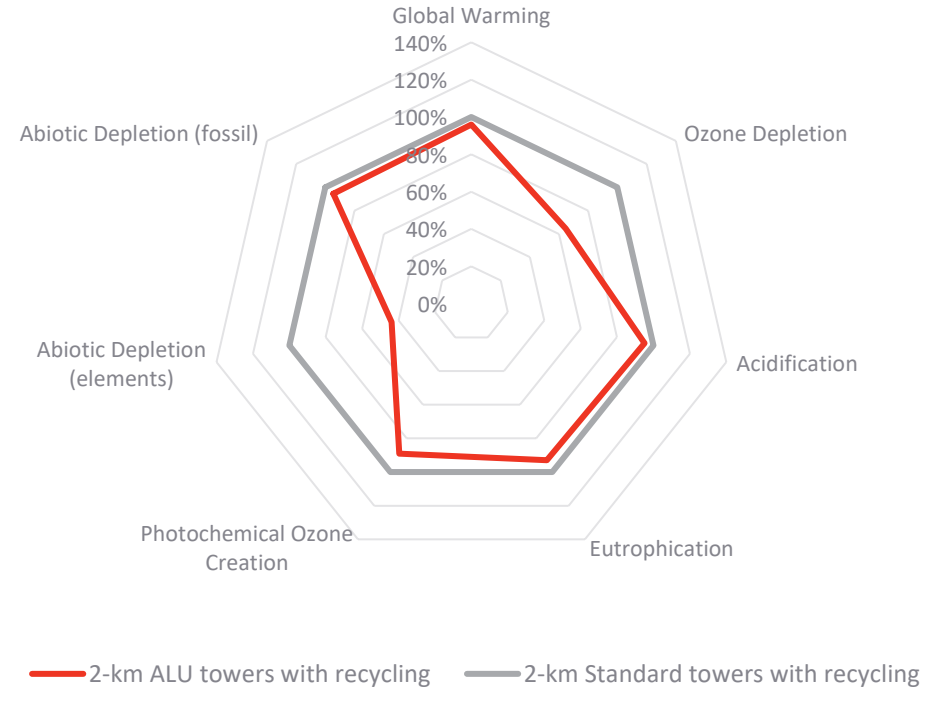




**FIGURE 15** Results for Scenario 1b, 2 km section with Aluminium tower as % of 2 km section with Standard steel tower, both with concrete foundations in mountain terrain. The figure above shows the gross results without benefits from recycling at the end of life stage, while the figure below shows net results accounting for recycling. Net impacts for Aluminium towers are similar to or less than the impacts for Standard steel towers in all impact categories.

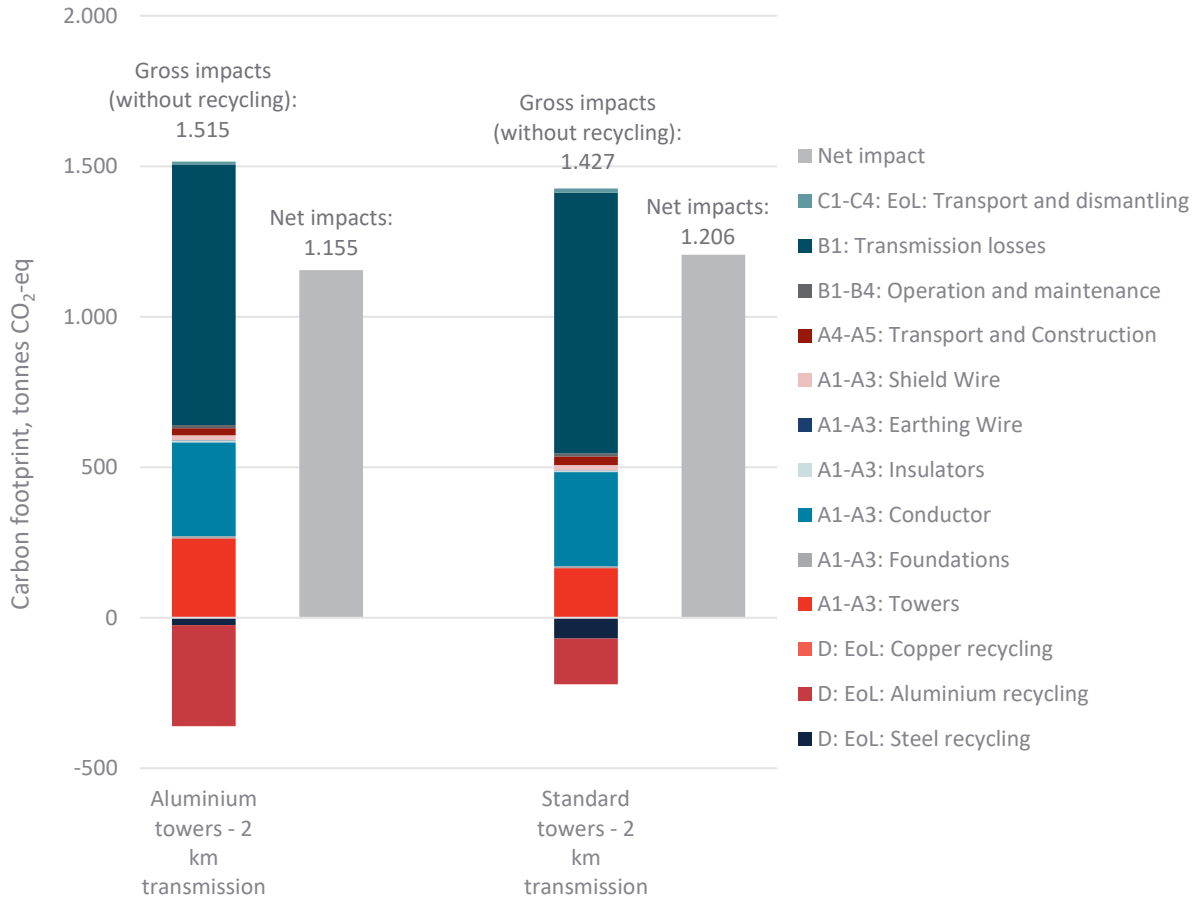



**FIGURE 16** Results for Scenario 1b, carbon footprint of a 2-km section with Standard steel towers and 2-km section with Aluminium towers.

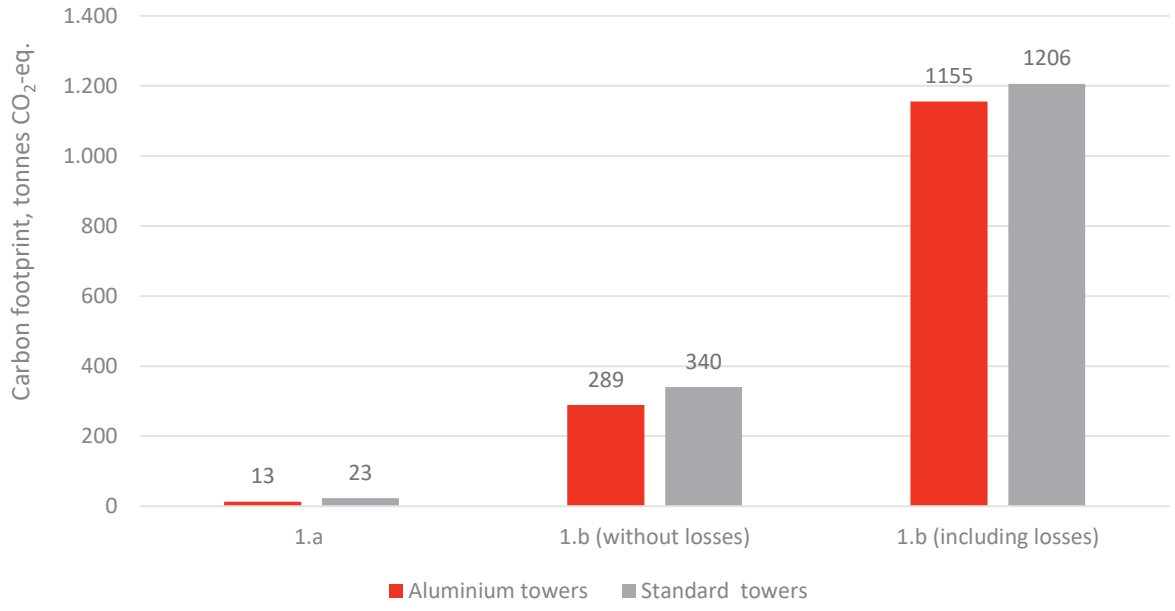



**FIGURE 17** Carbon footprint results of Aluminium and Standard steel towers for Scenarios 1a and 1b in mountainous terrain, with and without transmission losses.

## 4.2 Scenario 2: Two tower types in flat terrain

This chapter presents results for Scenario 2, i.e. for two different steel transmission towers in flat terrain, Standard steel and guyed M-tower, including foundations.

### 4.2.1 Scenario 2a: Standard steel and M-towers

The relative contribution of the different life cycle stages of the Standard steel and M-towers, including the prefabricated steel foundations, can be seen in Figures 18 and 19. In six out of seven categories, the manufacturing of the steel towers and steel foundations is a dominant contributor to environmental impacts. This is due to a material and energy intensive production process of primary steel. The galvanization of both steel towers and steel foundations (included) are also a significant factor in many categories, particularly in the abiotic depletion (elements) category, due to the mining of zinc. Fuel use during transport and construction (A4-A5) is also a significant contributor to many categories, particularly for acidification and eutrophication categories.

The M-tower is a lighter structure than the Standard steel tower, and it has two foundations instead of four. This explains the main differences between figures 18 and 19, where the foundations for M-towers have a smaller share of total impacts, albeit significant, which means that the fuel use during construction has a larger share. The two structures are in other respect very similar, as they are composed of the same materials.

When net results for both towers are compared, the M-tower has at least 40% lower impacts in all categories (Figure 20). The same difference is observed even though recycling is not considered, as the avoided burden from the recycling of towers is proportionally equivalent for both tower types.

When the carbon footprint of the two tower types are compared (Figure 21), the difference is mainly observed in the foundations, but also in the tower. The M-tower with its foundations has a 48% lower net carbon footprint than the Standard steel mast. The global warming impact of the M-tower foundations alone is approximately a third of the impacts of the Steel tower foundations. There is also a difference in the use of tracked vehicles and helicopter during construction, as the M-tower is transported via tracked vehicle and the Standard tower via helicopter from loading site to construction site. Both types of steel foundations are transported via tracked vehicle.

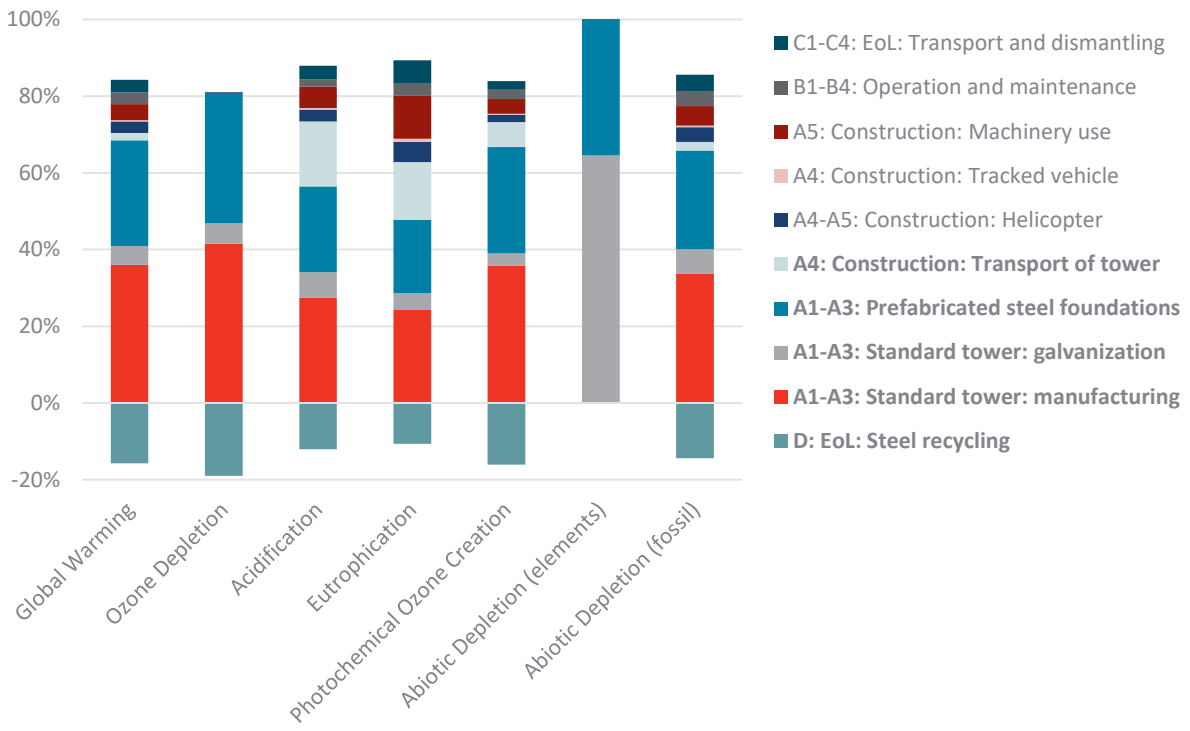



**FIGURE 18** Results for Scenario 2a, **Standard steel tower** with prefabricated steel foundations in **flat terrain**. The relative scale (100%) shows the contribution of different components to different impact categories.

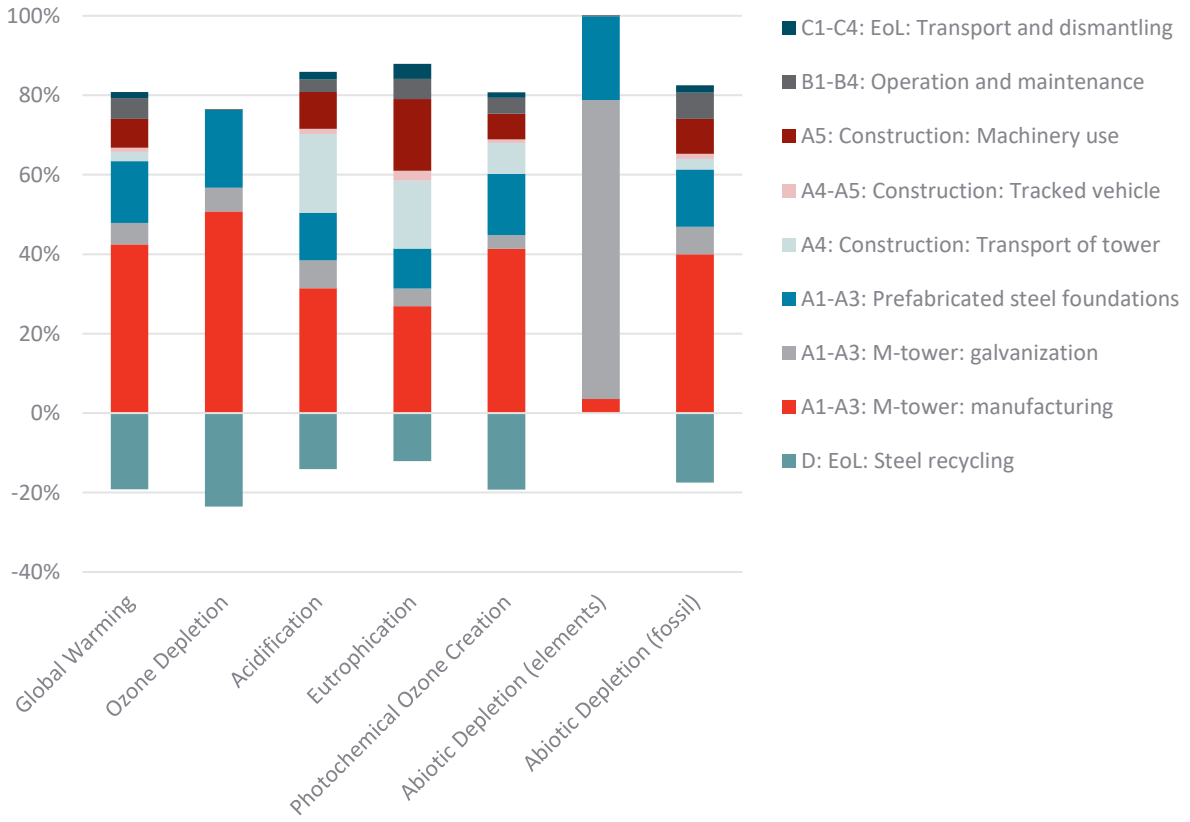



**FIGURE 19** Results for Scenario 2a, guyed **M-tower** with prefabricated steel foundations in **flat terrain**. The relative scale (100%) shows the contribution of different components to different impact categories.

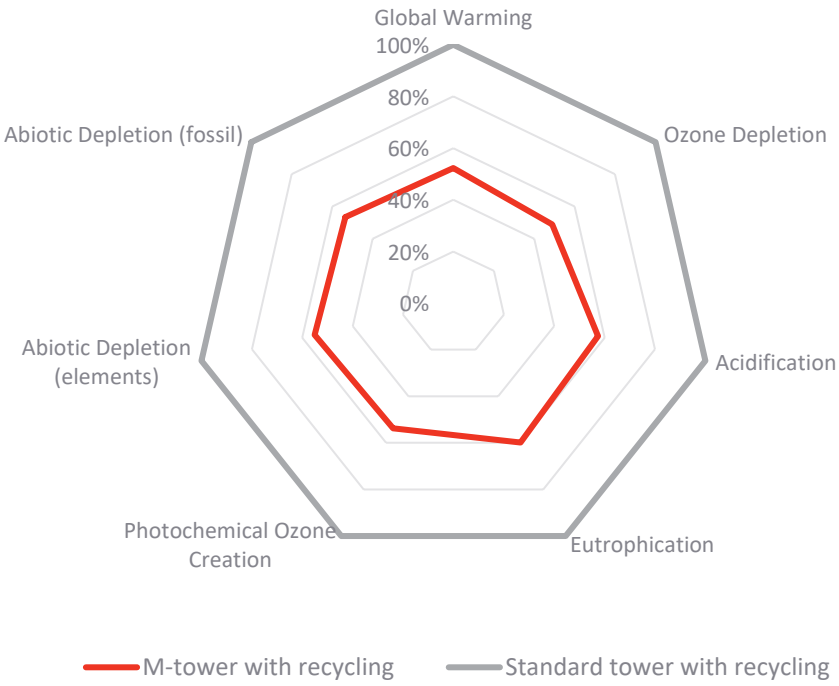



**FIGURE 20** Results for Scenario 2a, guyed M-tower as % of Standard steel tower, both with prefabricated steel foundations in flat terrain.

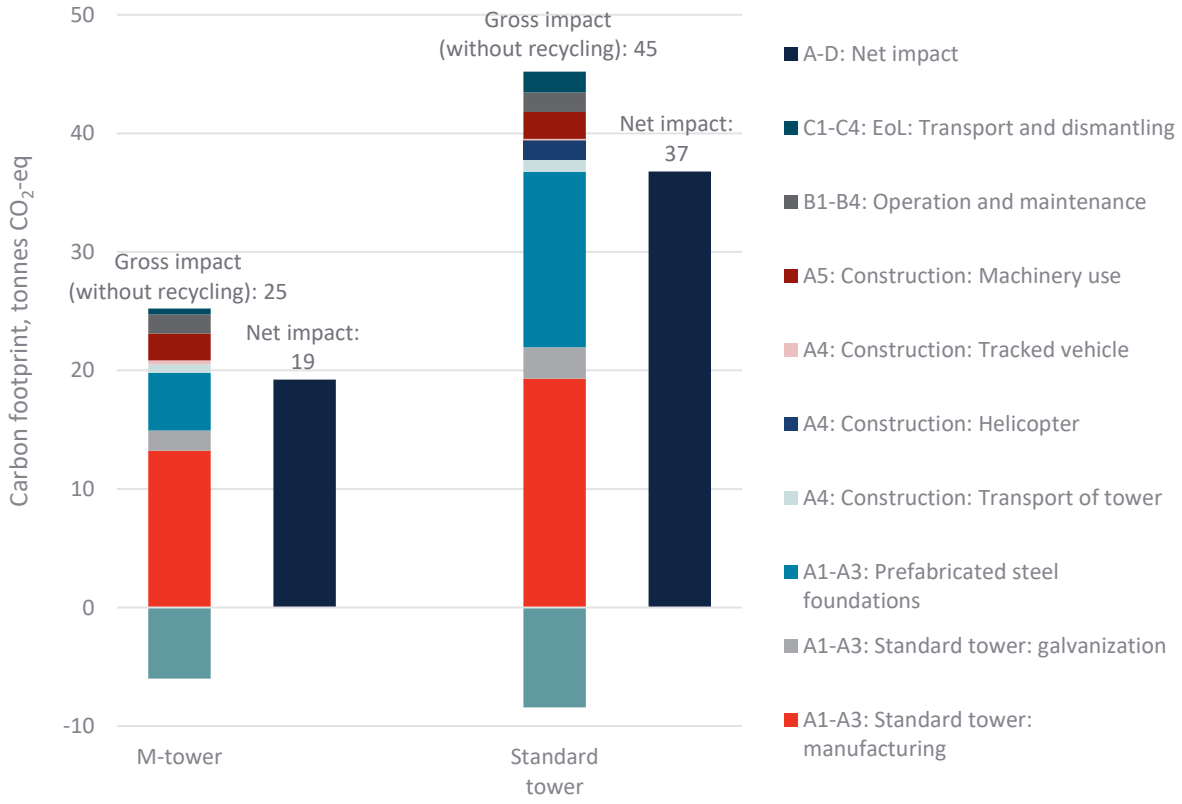



**FIGURE 21** Results for Scenario 2a, carbon footprint of the M tower and the Standard steel tower.

### 4.2.2 Scenario 2b: 2 km transmission with Standard steel and M-towers

A life cycle assessment was performed for a 2-km section of Standard steel towers and M-towers in flat terrain, including conductors, insulators, shield and earthing wires, see Figures 22 and 23. As was observed in scenario 1b, the conductors and transmission losses over a 70 year lifetime are dominant contributors to environmental impacts in five out of seven impact categories for both Standard towers and M-towers, i.e. in global warming, acidification, eutrophication, photochemical ozone creation and abiotic depletion (fossil).

When a 2-km section of the two tower types are compared (Figure 24), the M-tower has between 7 and 25% lower impacts than the Standard-tower in all impact categories. As the proportional amount of materials recycled is the same for both tower types, the same results (and identical figure) would be obtained if recycling were excluded.

In the global warming category (Figure 25), a 2-km section of M-towers in flat terrain has similar or a 7% lower impact than a 2-km section of Standard steel towers. If transmission losses were omitted, the M-towers would have a 22% lower impact than the Standard steel towers, see Figure 26.

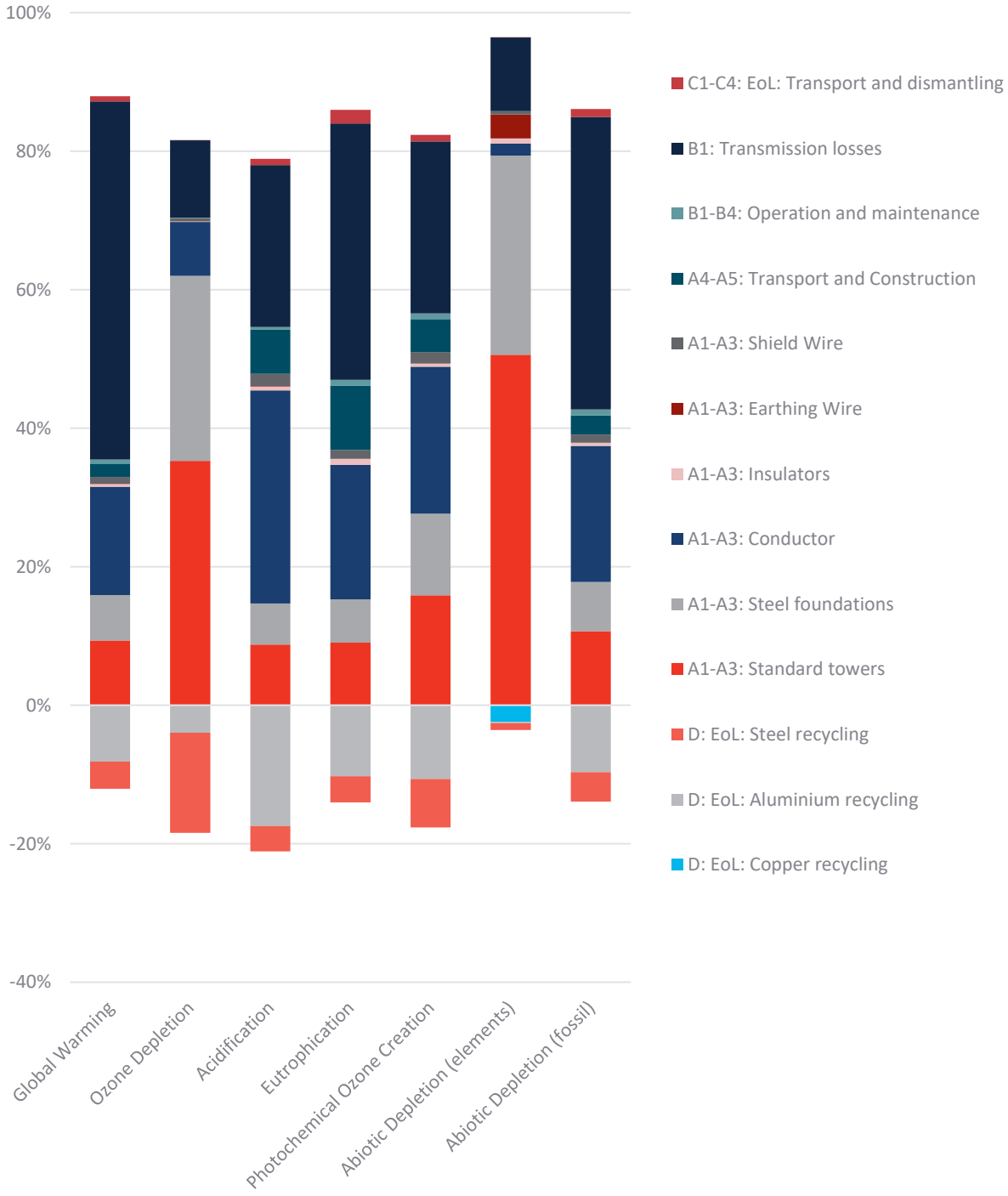



**FIGURE 22** Results for Scenario 2b, a 2-km line section of **Standard steel towers** with prefabricated foundations in flat terrain including the transmission losses. The line section includes five suspension towers and one tension tower, all Standard steel towers The relative scale (100%) shows the contribution of different components to different impact categories.

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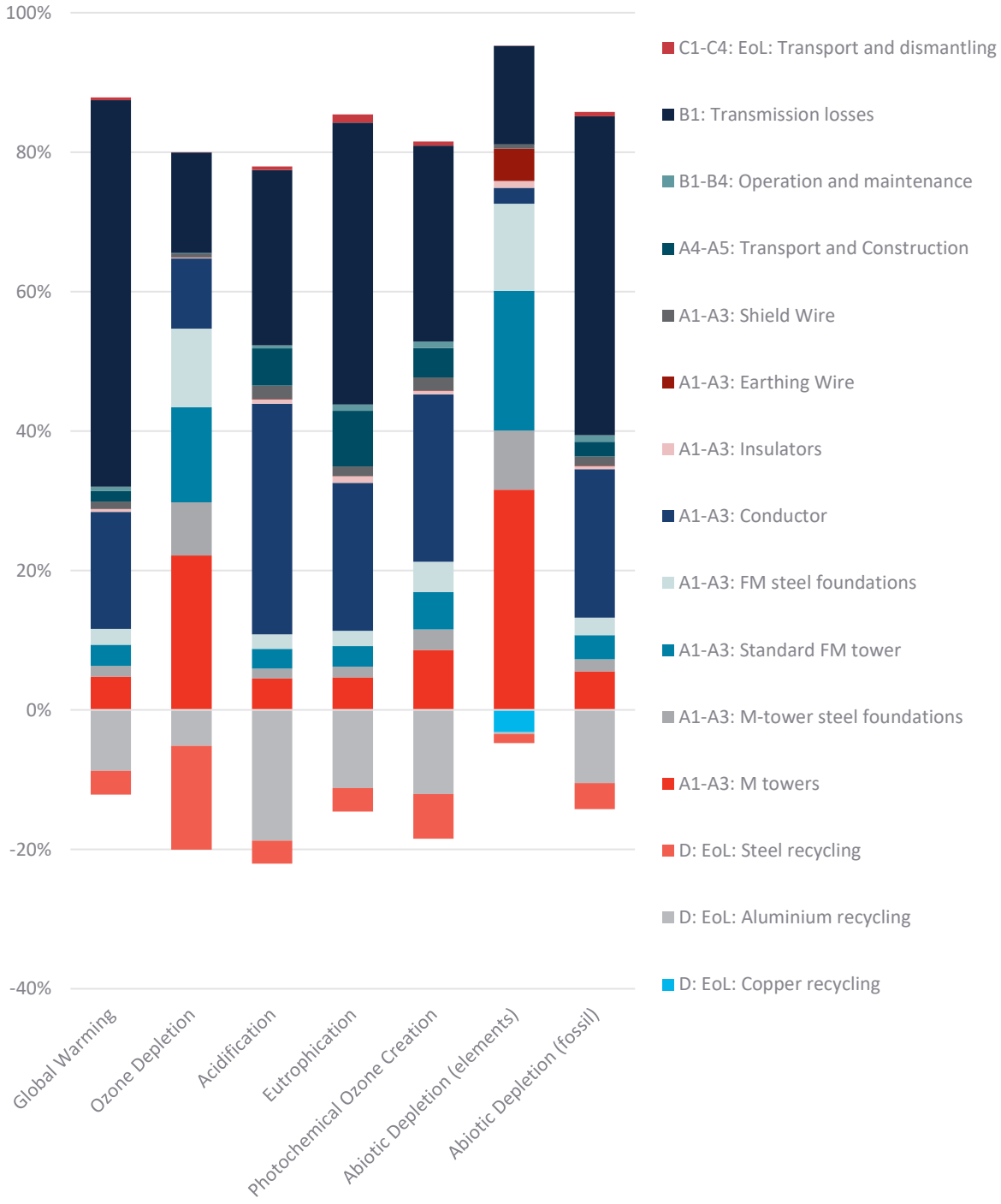


**FIGURE 23** Results for Scenario 2b, **M-tower** with prefabricated foundations in flat terrain including transmission losses. The line section includes five suspension towers, guyed M-towers, and one tension tower, which is a Standard steel tower. The relative scale (100%) shows the contribution of different components to different impact categories.

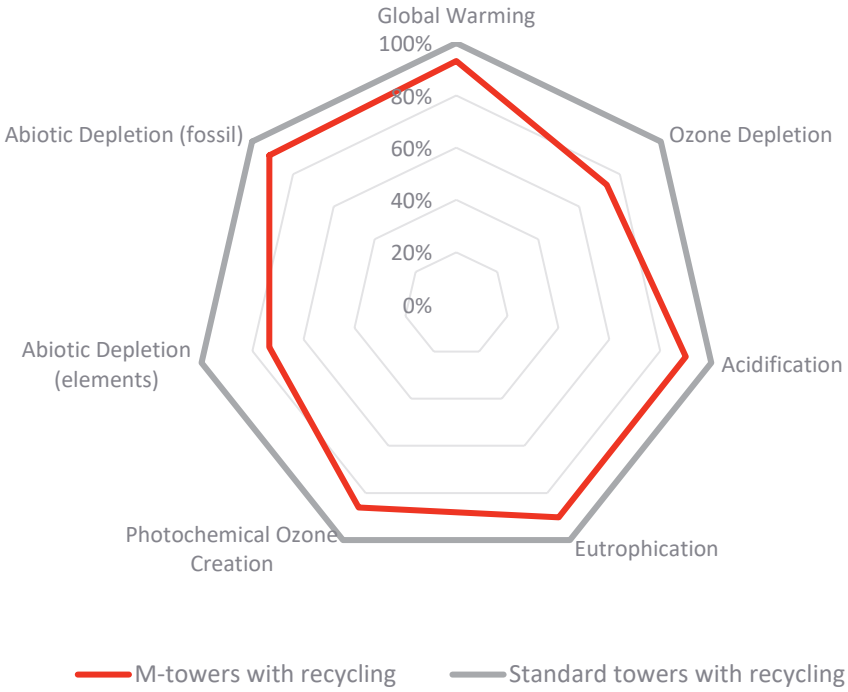


**FIGURE 24** Results for Scenario 2b, 2 km section with M tower as % of 2 km section with Standard steel tower (100%), both with prefabricated steel foundations in flat terrain. The figure shows the net results in every impact category (including recycling).

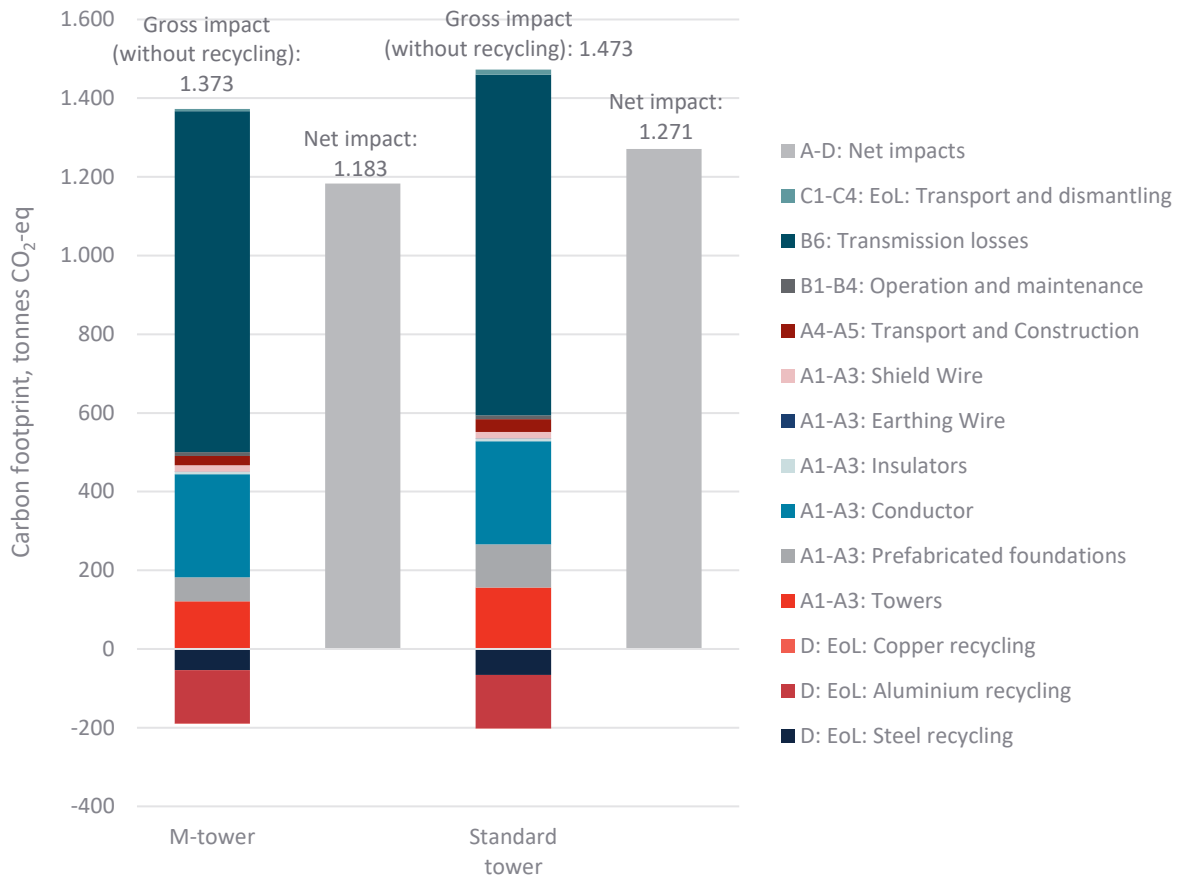


**FIGURE 25** Results for Scenario 2b, carbon footprint of the 2 km section with Standard steel tower and 2 km section with M tower.

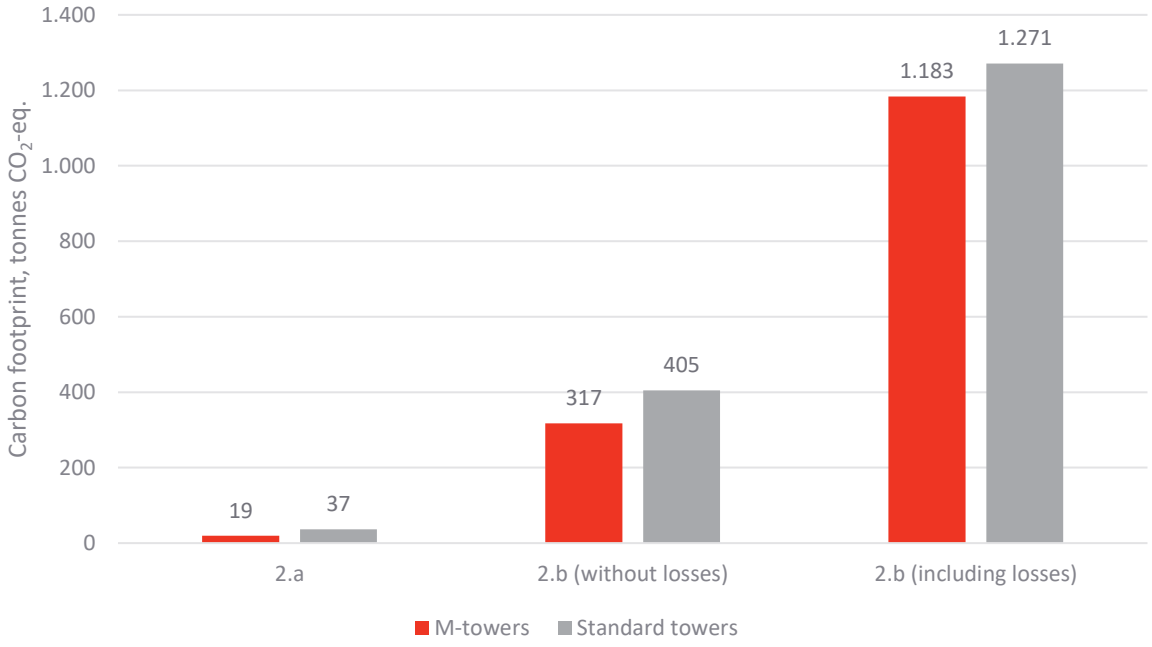


**FIGURE 26** Carbon footprint results of M-towers and Standard steel towers for Scenarios 2a and 2b in flat terrain, with and without transmission losses.

## 4.3 Scenario 3a: Two foundation types in flat terrain

This chapter presents results for Scenario 3a, i.e. for two different foundation types for the Standard steel tower in flat terrain; i.e. concrete foundations and prefabricated steel foundations.

### 4.3.1 Comparison of foundations

In the global warming impact category, the main difference between the two different foundation types lies in the materials used. Although a larger amount of concrete is needed for the concrete foundations than steel for the steel foundations per mast, see chapter 3.2, the carbon footprint of the steel foundations is almost five times higher than the concrete foundations, see Figure 27. On the other hand, while the steel tower and its concrete foundations are transported via helicopter from loading site to building site, the steel foundations are transported via tracked vehicle, resulting in considerable fuel use savings.

Since there is still a level of uncertainty about the fate of the steel foundations, results are shown with and without steel foundation recovery and recycling. This entails added fuel use during their excavation, transport and the added benefit of recycling. If the steel foundations are left in the ground, the net carbon footprint of the Standard tower with steel foundations is 28% higher than the same tower with concrete foundations. If the steel foundations are excavated and recycled, the net carbon footprint of the Standard tower with steel foundations is similar to its counterpart with concrete foundations, or approximately 6% higher. In other words, by excavating and recycling steel foundations, net carbon footprint savings of 6 tonnes $CO_2$-equivalents can be achieved per tower.

When the results are compared in other impact categories, recycling included, the steel foundations have a significantly higher impact (>10%) in three out of seven categories, i.e. Ozone Depletion, Abiotic Depletion (elements) and Photochemical Ozone Creation. In the four other categories, the net impacts are similar, i.e. the difference is within 6% of the Standard tower with concrete foundations.

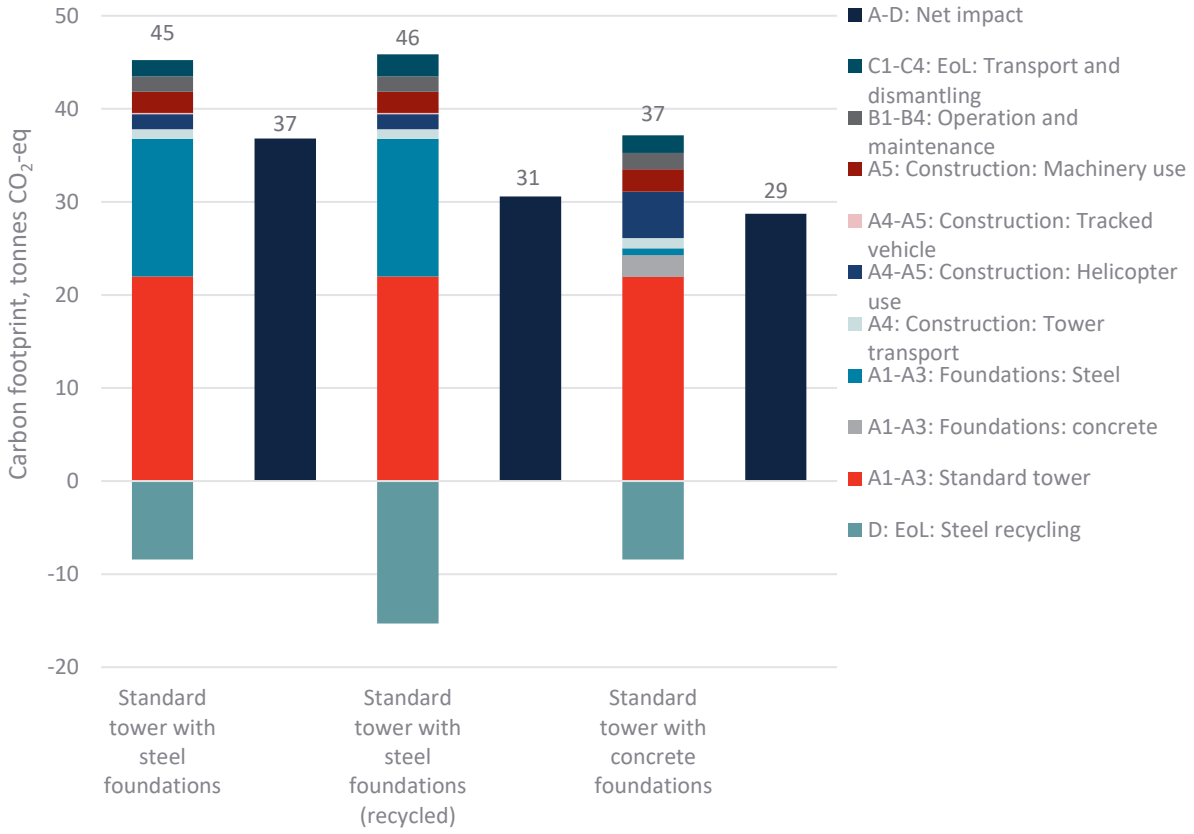


**FIGURE 27** Results for Scenario 3a, carbon footprint for Standard steel tower with prefabricated steel foundations and concrete foundations. Total gross and net impacts are displayed above the columns.

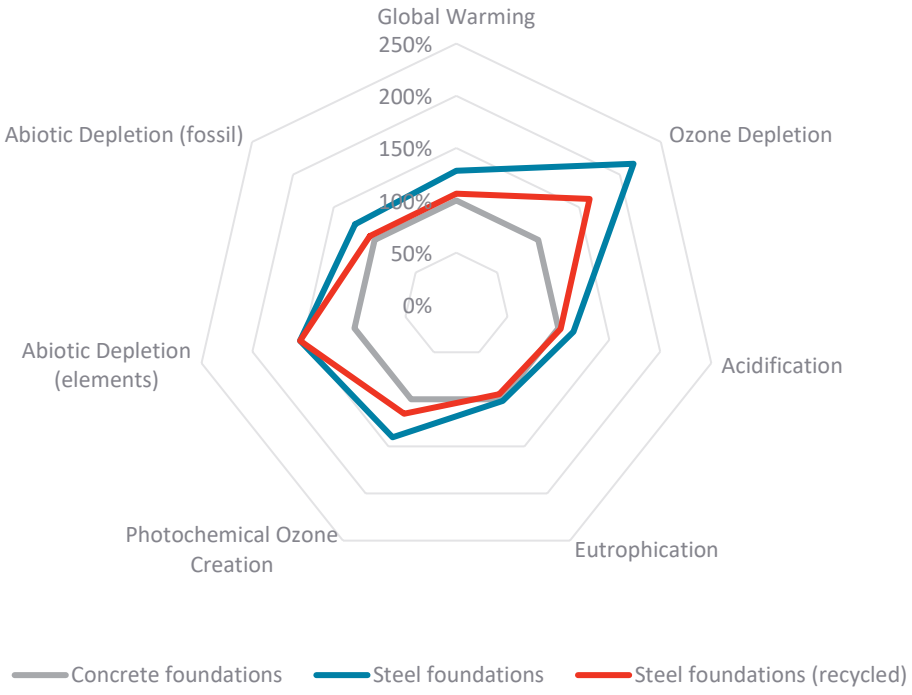


**FIGURE 28** Results for Scenario 3a, Standard steel tower with steel foundations as % of the same tower with concrete foundations in flat terrain (100%). The standard tower with steel foundations is presented with and without retrieval and recycling of foundations.

## 4.4 Summary of results

**TABLE 20** A summary of Scenario comparisons in all impact categories. The order of impact categories is the same as weighting and normalization results indicated (see chapter 5.1), with descending order of importance from left to right.

| Scenario | | Tower type and foundations | **Global Warming** | **Abiotic Depletion (fossil)** | Acidification | Photochemical Ozone Creation | Abiotic Depletion (elements) | Eutrophication | Ozone Layer Depletion |
|---|---|---|---|---|---|---|---|---|---|
| Scenario 1: Mountain terrain | 1a | Standard tower, concrete foundations | | | | | | | |
| | | Aluminium tower, concrete foundations | | | | | | | |
| | 1b | Standard towers 2-km line section | | | | | | | |
| | | Aluminium towers 2-km line section | | | | | | | |
| Scenario 2: Flat terrain | 2a | Standard tower, steel foundations | | | | | | | |
| | | M-tower, steel foundations | | | | | | | |
| | 2b | Standard towers 2-km line section | | | | | | | |
| | | M-towers 2-km line section | | | | | | | |
| Sc. 3: Flat terrain | 3a | Standard tower with steel foundations (recycled) | | | | | | | |
| | | Standard tower with concrete foundations | | | | | | | |

| Significantly worse results than comparison (>10% difference) | Significantly better results than comparison (>10% difference) | Similar results between two alternatives (<10% difference) |
|---|---|---|

# 5 CONCLUSION AND DISCUSSION

## 5.1 Data quality

The present study used high quality data, using background data from recognized international databases [7], data from manufacturers on material and energy use, and estimates and experience numbers from Statnett and EFLA. European averages were used for the sourcing of steel and aluminium, and for electricity use during manufacturing of towers. There is a level of uncertainty in calculations for all life cycle stages, but among the larger factors of uncertainty are lifetime expectancy, estimation of total transmission losses during the lifetime of the transmission line, and recycling assumptions for avoided burden.

## 5.2 Weighting and normalization

In order to better assess the importance or relevance of different impact categories, weighting and normalization can be applied to the results of an LCA. Normalization relates each impact to a reference of a per capita or a total impact for a given area for a given year. Weighting attaches a value to each of the normalized values, giving a value based importance of each impact. This can be based on political reduction targets or on the opinions of experts and/or laymen, for example [13].

In this study, CML 2001 normalization references are used (based on the year 2000) and calculated based on regional impacts, i.e. the impact of the European region (EU-25+3). Weighting is based on a questionnaire sent out by thinkstep in 2012 to experts worldwide [13], where they were asked to value the main environmental impact categories on a 1-10 scale.

The net results of scenario 1b (chapter 4.2.2) were normalized and weighted, see Figure 29. Two impact categories appear to have a greater importance than others, i.e. Global warming and Abiotic depletion (fossil). When the results of e.g. Aluminium towers have been normalized and weighted, 31% of the total regional equivalents of all seven impact categories can be attributed to the Global warming category. The Acidification, Photochemical ozone creation and Abiotic depletion (elements) categories also have a non-negligible impacts.

The normalized and weighted results indicate that when using the results of this study, an emphasis can be placed on the Global warming and Abiotic depletion (fossil) categories. Attention must also be payed to Acidification, Photochemical ozone creation and Abiotic depletion (elements) categories. The results also indicate that the Eutrophication and Ozone layer depletion categories are of less relevance compared to the other categories. In order to reflect these findings, the categories in Table 20, chapter 4.4, are presented in this same order.

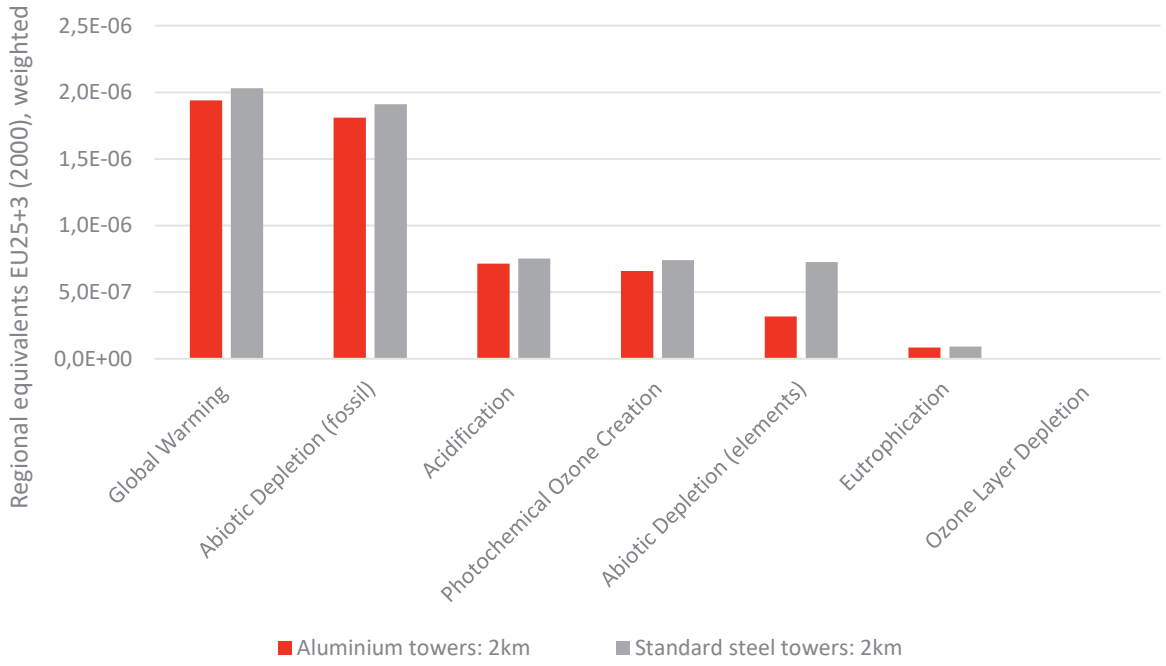


**FIGURE 29** Weighted and normalized impacts of a 2 km transmission section of a) Aluminium towers and b) Standard steel towers (scenario 1b, including transmission losses and recycling). Quantified impacts are compared to the average environmental impact of the European region (EU25+3, 2000) in one year (normalization, CML2000), and have been weighted according to the thinkstep LCIA Survey (2012), where impact categories were evaluated against each other based on importance.

## 5.3 Steel manufacturing

The steel and iron industry is both material and energy intensive. The two main routes used to produce steel are the blast oxygen furnace (BOF) route and the direct melting of scrap via electric arc furnace (EAF), the former consuming almost ten times more energy per ton liquid steel [14]. While the EAF route is dependent on the availability and cost of steel scrap, one of the benefits is that it requires far less energy for the production. The BOF route however can only use recycled steel to a limited extent (up to 30%), and needs raw materials such as iron, coal and limestone for the production. Furthermore, high quality steel alloys can only be produced in blast furnaces. While emissions from EAF generated steel are mainly a result of the carbon intensity of the electricity used, emissions from BOFs primarily arise from the reduction of the iron ore by the coke and oxygen in the blast furnace.

In this study, background data from the largest steel manufacturers, with sites all over Europe, was used to calculate the environmental impacts in different categories. This is compatible with information obtained from the three manufacturers for Statnett's LCI, where most steel came from European countries, see Figure 30. In 2016, approximately 60% of Europe's steel is produced via BOF

and 40% via EAF. Globally, the share of BOF produced steel is slightly higher or 74% vs 25% EAF produced steel [15]. Had generic data for global steel production been used (Figure 31), the net carbon footprint for the standard steel tower would have been approximately 24% higher.

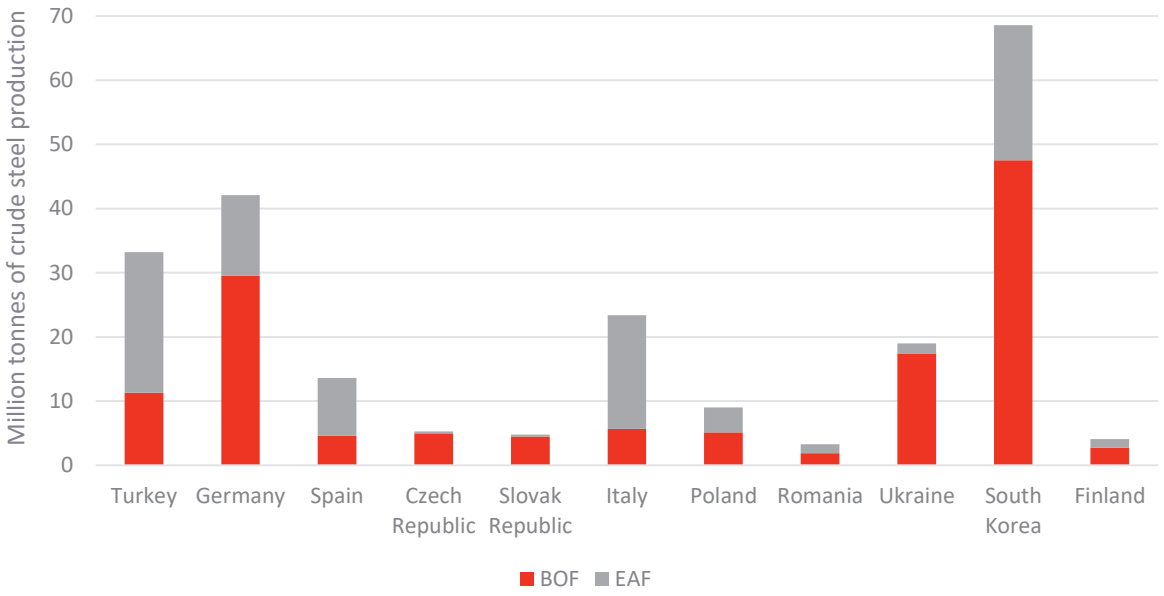


**FIGURE 30** Crude steel production by process in 2016 [15], blast oxygen furnace (BOF) and electric arc furnace (EAF). The countries shown are the main suppliers of steel for Statnett's steel tower manufacturers, based on data from three manufacturers.

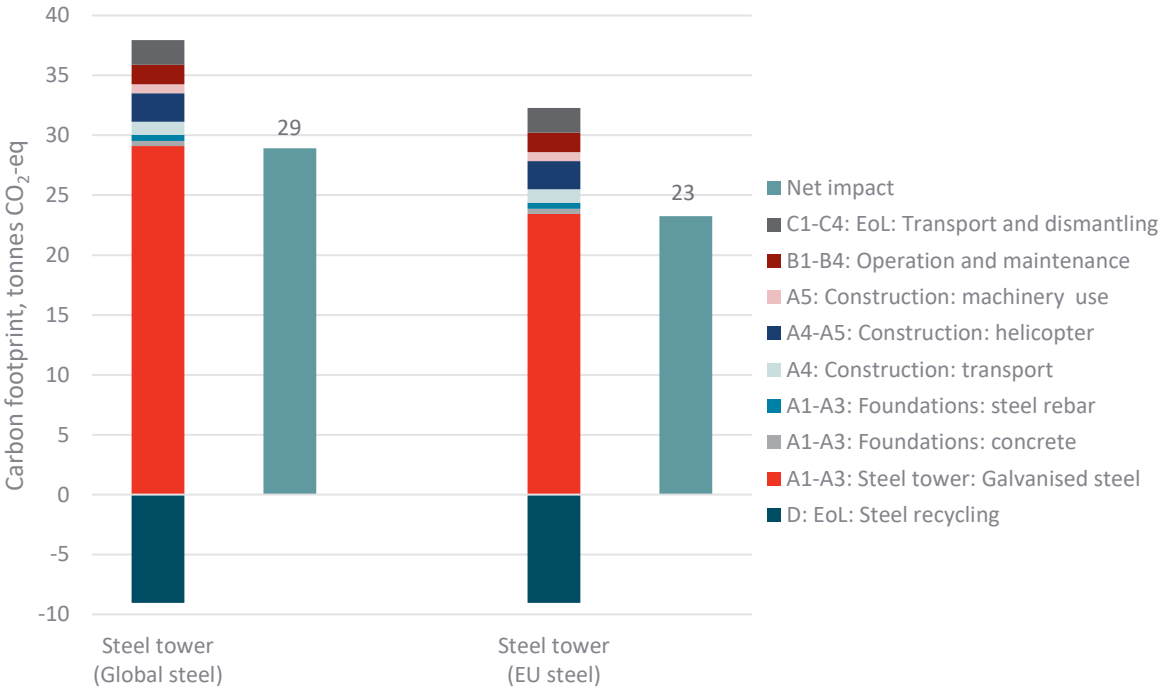


**FIGURE 31** Carbon footprint results for Scenario 1a, Standard steel tower with concrete foundations in mountain terrain, using a) generic data for global galvanized worldsteel and b) LCIA results from this study (see chapter 4.1.1).

## 5.4 Aluminium manufacturing

### 5.4.1 Source of aluminium

In 2017, China was the single largest producer of aluminium, producing around 50% of the world's aluminium according to reported numbers [16]. Around 12% of primary aluminium production took place in Europe during the same year. In 2013, Europe's largest source of electricity was nuclear power (27%) [7], while coal-based electrical capacity continues to dominate the grid mix in China (60-70%) during the last few years.

In this study, European primary aluminium ingot (EU-28), including imported and locally produced ingot, is used to manufacture Aluminium towers (scenario 1) and conductors (scenarios 1b and 2b). Using aluminium sourced from other parts of the world can significantly impact the total environmental impacts of the Aluminium tower, see Figure 32. As an example, global sourcing instead of European sourcing of aluminium can result in an 75% increase of total gross carbon footprint (excluding recycling). According to the IAI's latest environmental metrics report [17], the global warming potential of Global aluminium is 18 kg $CO_2$-eq. per kg of primary aluminium ingot, 20 kg $CO_2$-eq. for Chinese aluminium, 7 kg $CO_2$-eq. for European aluminium and 5 kg $CO_2$-eq. for North American aluminium (primarily from Canada). In countries or regions where hydropower is the dominant source of energy, e.g. in Norway, Quebec and Iceland, the net impact can be expected to decrease significantly.

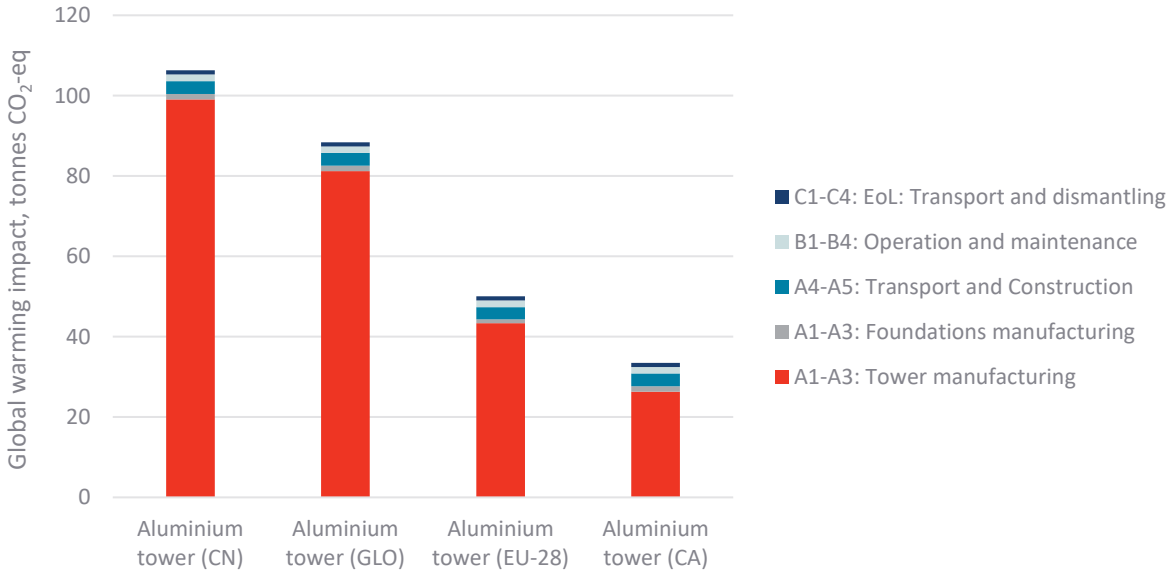


**FIGURE 32** Total global warming impact of the Aluminium tower, excluding recycling, depending on source of aluminium ingot. Transport of aluminium is in all cases assumed from mainland Europe, for simplification. Background data on aluminium production is based on thinkstep databases [7]. Impacts are shown for aluminium production in China (CN), world aluminium (GLO), European aluminium used in this study (EU-28) and Canadian aluminium (CA). Environmental impacts of global aluminium (GLO) is based on data collected and developed by the International Aluminium Institute (IAI) for the year 2010.

### 5.4.2 Anodising of aluminium

Anodizing is an electrochemical process that is used to increase the thickness of the natural oxide layer on the surface metal parts, creating a corrosion resistant, non-conductive finish. In the process, the smooth and light reflective metal surface can be transformed into a more matte surface, depending on the finish. The process entails pre-treatment and cleaning of the aluminium surface, followed by a bath where a direct current is passed through an electrolytic solution, with the aluminium object serving as the anode. The current releases hydrogen at the cathode and oxygen at the surface of the aluminium anode, creating a build-up of aluminium oxide.

Aluminium towers are still in development at Statnett. Anodizing can result in a more matte surface, reflecting less light and therefore minimizing visual impacts, and it can also provide better adhesion for paint primers and coatings. The anodizing process however requires electricity and thermal energy, of which environmental impacts are country specific. Energy and material use furthermore depends on the desired thickness of anodic layer.

Using generic data for anodization (20 µm) from Germany, it is observed that anodization of aluminium profiles (European aluminium) increases the net carbon footprint nearly threefold, see Figure 33. Net impacts are increased in every impact category, see Figure 34. These results can however only serve as an indicator of net impacts, and any decision making must be based on more specific data, e.g. on use of energy, anodization thickness, technology used, etc., preferably from manufacturer.

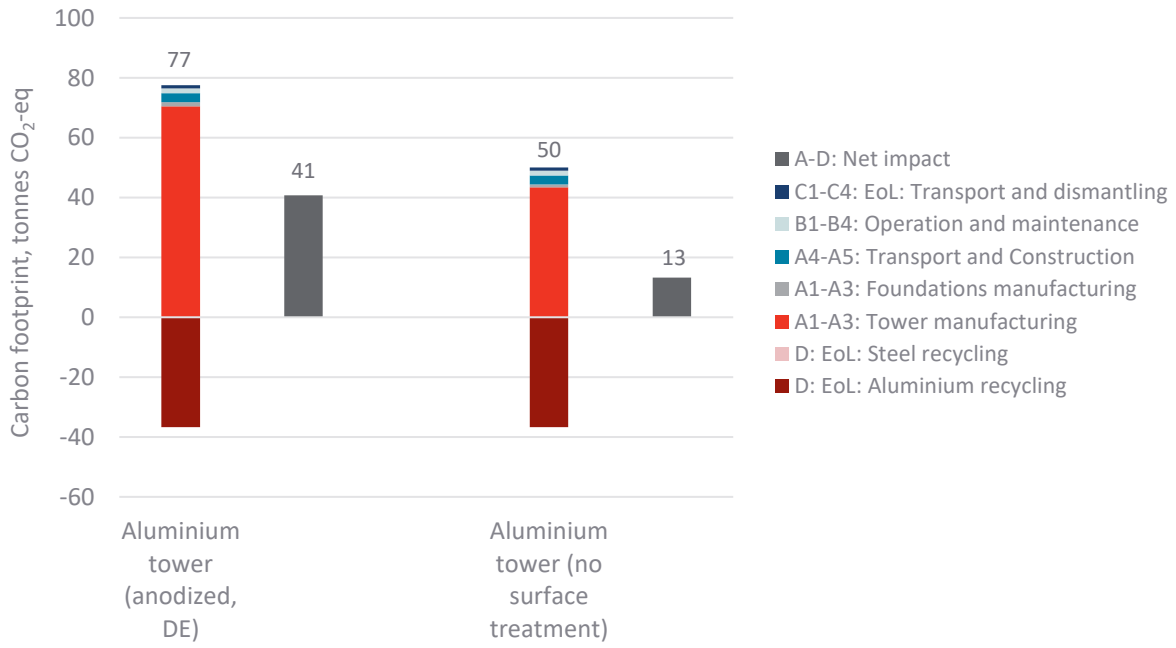


**FIGURE 33** Carbon footprint of Aluminium towers (anodized aluminium profiles vs non-anodized profiles, using EU-28 aluminium ingot mix) and Standard steel towers, including their foundations. Background information on aluminium anodization is based on German data, using the electricity grid mix and thermal energy from Germany [7].

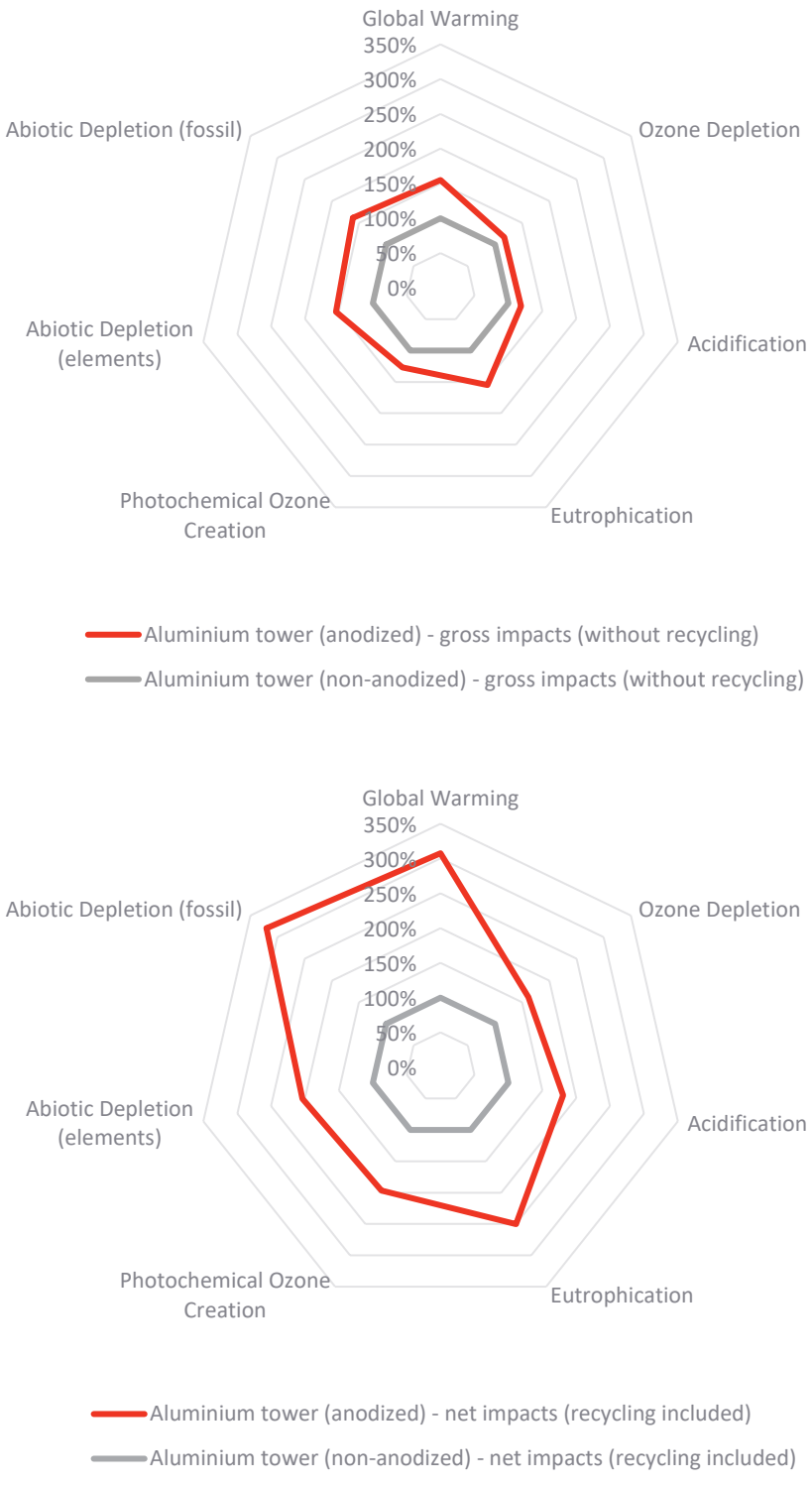


**FIGURE 34** Anodized aluminium tower as % of Aluminium tower without surface treatment. The top figure shows the difference between the two towers where benefits from recycling are not included (gross impacts), and the bottom figure shows the difference between the two towers including benefits from recycling (net impacts).

## 5.5 Transport methods

For this study, manufacturers provided two transport routes of towers, by sea and by land. Sea transport was chosen by default in the study as this is the most common mode of transport. It is also established that rail transport (by land) has a higher emission intensity per tonne-kilometre compared to shipping [18]. For the sake of comparison, the carbon footprint of the Standard steel tower in mountain terrain (Scenario 1a) was also calculated assuming non-oceanic transport of the tower. Average transport distances assumed for land transport of Standard towers can be seen in Table 21 here below, using the same three manufacturers that were used to calculate average sea-transport distances (see table 13 in chapter 3.4.1).

For the heaviest tower, the Standard steel tower, the results of the study reveal that the share of tower transport in the global warming impact is 3% (gross impacts, recycling excluded, see chapter 4.1.1). Had shipping been replaced by road transport only, this share would increase to 5% (Figure 35), i.e. an increase from tower transport emissions by 43% or by almost 500 kg $CO_2$-equivalents. The net carbon footprint of the Standard tower would furthermore have increased by 2%. Interestingly, the global warming impact of helicopter use during the construction of each tower, from loading site to construction site, is 2.4 tonnes $CO_2$-equivalents, which is a larger contributor than the transport of the tower from manufacturer to loading site.

**TABLE 21** Average transport distances assumed for the non-oceanic transport of towers, from manufacturer to warehouse in Norway. Numbers are average transport distances based on information from three manufacturers (in Turkey, Croatia and Finland).

| TRANSPORT | MODE OF TRANSPORT | DISTANCE [KM] |
|---|---|---|
| From manufacturer to warehouse, NO | Truck-trailer | 2847 |

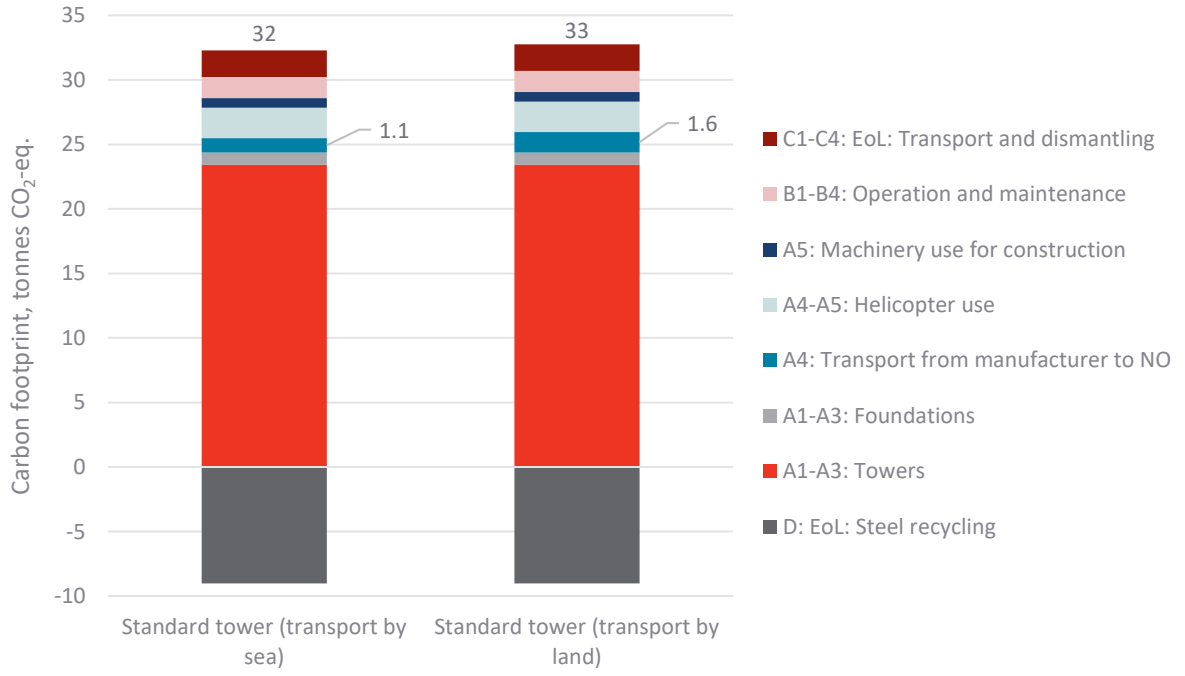


**FIGURE 35** Carbon footprint of Statnett's standard steel tower with concrete foundations in mountain terrain (Scenario 1a), where the tower has been transported from manufacturer to loading site via a) ship route, b) land route. Data is based on average transport distances from manufacturers, see chapter 3.4.1 and 5.5.

## 5.6 End-of-life impacts and recycling

The results of this study are clear when recycling of metals is concerned. Material recovery and recycling at the end of a tower's life cycle can benefit other systems and future generations, conserving energy and other natural resources. In this study, European market-based ratios were used to calculate the avoided burdens when recycling steel and aluminium. The price ratio of aluminium scrap to primary aluminium is higher than the price ratio of steel scrap to primary steel [7], which explains why higher avoided burdens are calculated for aluminium than for steel in this study. This ratio can obviously change in the future and can be more region or country specific, if relevant. With better waste treatment technologies, higher recycling ratios and a transition towards renewable energy sources, it is expected that recycling benefits will increase in all impact categories. This will go hand in hand with better production technologies and lower impacts of virgin metal production.

The results demonstrate the importance of material recovery and recycling for all impact categories, particularly in the case of towers and conductors. For the current assumptions, the recycling of aluminium reduces the gross carbon footprint of the Aluminium tower alone (Scenario 1a) by 73%. The recycling of steel reduces the gross carbon footprint of the Standard steel tower (Scenario 1a) by 28%. In a larger context, the recycling of metals reduces the gross carbon footprint of a 2-km section of Aluminium towers by 24% and Steel towers by 15%. The results of this study also demonstrate the importance and relevance of material recovery when steel foundations are concerned. For future generations, it is profitable from an environmental point of view to excavate and recover steel foundations at the end of a tower's life time. Improved management of natural resources delivers real benefits, not only for the environment but also for the economy, society and human health, reducing the need for primary production.

## 5.7 Comparison with other studies and use of results

The large share of conductors and transmission losses in the total environmental impacts of the transmission system has already been demonstrated in earlier studies, e.g. in a study of regional electricity transmission in Norway [19] and of the overhead transmission system in Iceland [20]. Overhead transmission structures (particularly conductors), underground cables, transmission losses, transformers and switchgear were in the above studies among the largest contributors to environmental impacts in all categories. The results of Scenarios 1b and 2b are also in agreement with earlier preliminary studies on a 420-kV transmission line in Statnett's transmission system, where the manufacturing of conductors and transmission losses dominate most impact categories [21]. In the present study, only a delimited segment of the transmission system was assessed from a life cycle perspective, as the purpose of the study was to analyse and compare new tower types and foundations with the current standard infrastructure.

The results of this study are useful in targeting areas where improvement can be made. One of the recent changes made to the ISO 14001:2015 environmental management system standard is a requirement for organizations to consider a life cycle perspective of the products or services it provides. It is in other words a requirement to introduce life cycle thinking to design and development stages, procurement, operation and maintenance and end of life stages, not only ensuring that the

upstream supply chain is practicing the same habits, but also overseeing sustainable management of resources at the end of a product's service life.

Informed sourcing of materials for tower manufacturing is critical in minimizing environmental impacts of the tower structure, and this study can be used as a tool to develop best practices in sustainable procurement. As an example, one way of ensuring responsible sourcing of materials is to ask for and compare third-party verified Environmental Product Declarations (EPDs) or Product Carbon Footprints from tower manufacturers. The results of this study can also prove useful for other strategic decisions at Statnett, e.g. for the choice of towers and choice of foundations. Finally, the results provide an insight into the benefits of material recovery and recycling at the end of a towers' life cycle. The study and its life cycle inventory also provide a basis for further analyses or comparisons, and a basis for further communication, e.g. the development of an EPD for electricity transmission at Statnett.

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# APPENDIX A LIFE CYCLE IMPACT CATEGORIES

**TABLE A.1** A short description of environmental impact categories used in the study, as required by the EN 15804 standard. Adapted from guidelines from the Danish EPA [22] and the GaBi Database & Modelling Principles [13].

| | |
|---|---|
| Global Warming Potential (GWP 100 years) | Global warming – or "greenhouse effect" / "climate change" – addresses the effect of increasing temperature in the lower atmosphere. The atmosphere is normally heated by incoming radiation from the sun. A part of the radiation is normally reflected by the surface of the Earth but the atmosphere's content of carbon dioxide ($CO_2$) and other "greenhouse" gasses, e.g. methane ($CH_4$), nitrous oxide ($N_2O$) and chlorofluorocarbons (CFCs), reflects or absorbs the IR-radiation resulting in the greenhouse effect, i.e. an increase of temperature in the lower atmosphere to a level above normal. The possible consequences of the greenhouse effect include an increase of the temperature level leading to melting of the polar ice caps and glaciers in mountain area, resulting in elevated sea levels, increased intensity as well as frequencies of storms and increased number and length of draught. The global warming potential is calculated in carbon dioxide equivalents ($CO_2$-eq.), meaning that the greenhouse potential of an emission is given in relation to $CO_2$. Since the residence time of gases in the atmosphere is incorporated into the calculation, a time range for the assessment must also be specified. A usual period is 100 years. |
| Ozone Layer Depletion Potential (ODP, steady state) | Ozone ($O_3$) is created in the stratosphere by the disassociation of oxygen atoms that are exposed to short-wave UV-light. This leads to the formation of the so-called ozone layer in the stratosphere (15-50 km high). About 10% of this ozone reaches the troposphere through mixing processes. A number of substances, some of which occur naturally in the stratosphere, are involved in the breakdown of ozone: long-lived chlorine and bromine compounds, methane ($CH_4$), nitrous oxide ($N_2O$), and water vapour $H_2O$. The atmosphere receives ultraviolet radiation from the sun. Ozone molecules in the stratosphere absorb large quantities of this UV radiation, thus removing the life-threatening UV-C radiation and reducing the harmful UVB radiation. The reduction in the ozone concentration in the stratosphere will probably have a serious effect on the life on the surface of the Earth, causing damage to plants, animals, and humans. In the area around the South Pole (which is considered to be the most affected) effects on phytoplankton have been observed. Phytoplankton is a primary producer in every aquatic food chain and consequences can therefore be expected to be dramatic. The ozone depletion will also effect humans in the form of skin cancer, reduced immune defence etc. |
| Acidification Potential (AP) | Acidification is regarded as a regional effect. The acidification of soils and waters occurs predominantly through the transformation of air pollutants into acids. This leads to a decrease in the pH-value of rainwater and fog from 5.6 to 4 and below. Sulphur dioxide and nitrogen oxide and their respective acids ($H_2SO_4$ und $HNO_3$) produce relevant contributions. Ecosystems are damaged, so forest dieback is the most well-known impact. In certain areas, acidification leads to increased mobility of heavy metals and aluminium. In the terrestrial ecosystem the effects are seen in softwood forests (e.g. spruce) but also in hardwood forests (e.g. beech) as inefficient growth and as a final consequence forest dieback. In Europe, these effects are mainly seen in Scandinavia and in the middle/eastern part of Europe. In the aquatic ecosystem the effects are seen as (clear) acid lakes without any wildlife. Clean lakes are mainly seen in Scandinavia. Buildings, constructions, sculptures and other objects are also damaged by e.g. acid rain. |

| | |
|---|---|
| Eutrophication Potential (EP) | Eutrophication is regarded as a regional effect. Eutrophication is the enrichment of nutrients in a certain place. Eutrophication can be aquatic or terrestrial. Air pollutants, wastewater and fertilisation in agriculture all contribute to eutrophication. The result in water is an accelerated algae growth, which in turn, prevents sunlight from reaching the lower depths. This leads to a decrease in photosynthesis and less oxygen production. Oxygen is also needed for the decomposition of dead algae. Both effects cause a decreased oxygen concentration in the water, which can eventually lead to fish dying and to anaerobic decomposition (decomposition without the presence of oxygen). Hydrogen sulphide and methane are produced. This can lead to the destruction of the eco-system, among other consequences. On eutrophicated soils, an increased susceptibility of plants to diseases and pests is often observed, as is degradation of plant stability. If the nutrification level exceeds the amounts of nitrogen necessary for a maximum harvest, it can lead to an enrichment of nitrate. This can cause, by means of leaching, increased nitrate content in groundwater. Nitrate also ends up in drinking water. Nitrate at low levels is harmless from a toxicological point of view. Nitrite, however, is a reaction product of nitrate and toxic to humans. |
| Photochem. Ozone Creation Potential (POCP) | Despite playing a protective role in the stratosphere, ozone at ground level is classified as a damaging trace gas and one of the most important environmental threats on the regional scale. Ozone is formed in the troposphere under the influence of sunlight when nitrogen oxides are present. When VOC's are also present, peroxy radicals can be produced, which are are highly reactive and toxic compounds. Ozone is a secondary pollutant, as there is practically no ozone present in source emissions derived from human activity. At high concentrations it is hazardous to human health, but already at lower concentrations it causes damage to vegetation. Ozone is a transboundary pollutant, and it can be produced or consumed by other pollutants during transport over long ranges. The health problems caused by ozone have generally been considered to be an effect of the very high peaks of ozone concentration, known as ozone episodes. Increased background levels of ozone cause damage to vegetation, and thereby ozone also imposes an economic threat through a potential reduction of crop yield. |
| Abiotic Depletion (ADP elements and ADP fossil) | The abiotic depletion potential (ADP) covers some selected natural resources as metal-containing ores, crude oil and mineral raw materials. Abiotic resources include raw materials from non-living resources that are non-renewable. This impact category describes the reduction of the global amount of non-renewable raw materials. Non-renewable means a time frame of at least 500 years. The abiotic depletion potential is split into two sub-categories, elements and fossil.<br><br>Abiotic depletion potential (elements) covers an evaluation of the availability of natural elements like minerals and ores, including uranium ore. The reference substance for the characterisation factors is antimony. Two calculations of ADP (elements) from CML are integrated in GaBi, one based on ultimate resources (i.e. the total mineral content in the earth crust) and one based on what is evaluated as being economically feasible to extract. The latter version is recommended by ILCD.<br><br>The second sub-category is abiotic depletion potential (fossil), which includes the fossil energy carriers (crude oil, natural gas, coal resources) all listed in MJ of lower calorific value. Uranium is accounted for in ADP (elements) and is not listed as a fossil fuel. |

# APPENDIX B LCIA RESULTS

**TABLE B.1** Numerical LCIA results for **Standard steel towers with concrete foundations, in mountain terrain (Scenario 1a).** Results are presented per transmission tower (suspension tower). All methods are CML 2001 (Version January 2016). A description of impact categories can be seen in Appendix A.

| | A1-A3: STEEL TOWER: MANUFACTURING | A1-A3: STEEL TOWER: GALVANIZATION | A1-A3: FOUNDATIONS: CONCRETE | A1-A3: FOUNDATIONS: STEEL REBAR | A4: CONSTRUCTION: TRANSPORT OF TOWER | A4-A5: CONSTRUCTION: HELICOPTER | A5: CONSTRUCTION: MACHINERY USE | B1-B4: OPERATION AND MAINTENANCE | C1-C4: EOL: DISMANTLING AND TRANSPORT | D: EOL: STEEL RECYCLING | A-D: NET IMPACTS |
|---|---|---|---|---|---|---|---|---|---|---|---|
| Global Warming Potential (GWP 100 years), excl biogenic carbon [kg CO2 eq.] | 2,1E+4 | 2,8E+3 | 4,4E+2 | 5,1E+2 | 1,1E+3 | 2,4E+3 | 7,4E+2 | 1,6E+3 | 2,1E+3 | -9,0E+3 | 2,3E+4 |
| Ozone Layer Depletion Potential (ODP, steady state) [kg R11 eq.] | 1,6E-6 | 2,0E-7 | 1,6E-9 | 5,7E-9 | 4,3E-10 | 5,1E-10 | 5,7E-10 | 1,1E-9 | 5,4E-10 | -7,2E-7 | 1,1E-6 |
| Acidification Potential (AP) [kg SO2 eq.] | 4,1E+1 | 1,0E+1 | 7,8E-1 | 1,5E+0 | 2,6E+1 | 6,5E+0 | 2,6E+0 | 2,7E+0 | 5,7E+0 | -1,8E+1 | 7,9E+1 |
| Eutrophication Potential (EP) [kg Phosphate eq.] | 4,4E+0 | 7,9E-1 | 1,2E-1 | 1,4E-1 | 2,7E+0 | 1,3E+0 | 6,2E-1 | 5,3E-1 | 1,2E+0 | -1,9E+0 | 9,9E+0 |
| Photochem. Ozone Creation Potentia (POCP) [kg Ethene eq.] | 7,7E+0 | 7,0E-1 | 8,6E-2 | 1,9E-1 | 1,4E+0 | 5,9E-1 | 2,5E-1 | 4,9E-1 | 5,2E-1 | -3,5E+0 | 8,5E+0 |
| Abiotic Depletion (ADP elements) [kg Sb eq.] | 3,4E-3 | 2,3E+0 | 7,2E-4 | 2,5E-2 | 4,6E-5 | 7,1E-5 | 6,3E-5 | 9,7E-5 | 7,2E-5 | -1,5E-3 | 2,3E+0 |
| Abiotic Depletion (ADP fossil) [MJ] | 2,1E+5 | 3,9E+4 | 1,8E+3 | 5,5E+3 | 1,4E+4 | 3,3E+4 | 9,6E+3 | 2,2E+4 | 2,8E+4 | -8,8E+4 | 2,7E+5 |

**TABLE B.2** Numerical LCIA results for **Aluminium towers with concrete foundations, in mountain terrain (Scenario 1a).** Results are presented per transmission tower (suspension tower). All methods are CML 2001 (Version January 2016). A description of impact categories can be seen in Appendix A.

| | A1-A3: ALUMINIUM TOWER MANUFACTURING | A1-A3: FOUNDATIONS: CONCRETE | A1-A3: FOUNDATIONS: STEEL REBAR | A4: CONSTRUCTION: TRANSPORT OF TOWER | A4-A5: CONSTRUCTION: HELICOPTER | A5: CONSTRUCTION: MACHINERY USE | B1-B5: OPERATION AND MAINTENANCE | C1-C4: EOL: DISMANTLING AND TRANSPORT | D: EOL: STEEL RECYCLING | D: EOL: ALUMINIUM RECYCLING | A-D: NET IMPACTS |
|---|---|---|---|---|---|---|---|---|---|---|---|
| Global Warming Potential (GWP 100 years), excl biogenic carbon [kg CO2 eq.] | 4,3E+4 | 4,4E+2 | 5,1E+2 | 5,0E+2 | 1,8E+3 | 7,4E+2 | 1,6E+3 | 1,0E+3 | -7,6E+1 | -3,7E+4 | 1,3E+4 |
| Ozone Layer Depletion Potential (ODP, steady state) [kg R11 eq.] | 4,9E-7 | 1,6E-9 | 5,7E-9 | 2,0E-10 | 3,8E-10 | 5,7E-10 | 1,1E-9 | 3,1E-10 | -5,9E-10 | -3,6E-7 | 1,4E-7 |
| Acidification Potential (AP) [kg SO2 eq.] | 2,1E+2 | 7,8E-1 | 1,5E+0 | 1,2E+1 | 4,8E+0 | 2,6E+0 | 2,7E+0 | 3,0E+0 | -3,2E-1 | -1,9E+2 | 5,6E+1 |
| Eutrophication Potential (EP) [kg Phosphate eq.] | 1,3E+1 | 1,2E-1 | 1,4E-1 | 1,2E+0 | 9,9E-1 | 6,2E-1 | 5,3E-1 | 6,3E-1 | -2,3E-2 | -1,1E+1 | 6,1E+0 |
| Photochem. Ozone Creation Potentia (POCP) [kg Ethene eq.] | 1,2E+1 | 8,6E-2 | 1,9E-1 | 6,4E-1 | 4,4E-1 | 2,5E-1 | 4,9E-1 | 2,7E-1 | -2,1E-2 | -1,0E+1 | 3,9E+0 |
| Abiotic Depletion (ADP elements) [kg Sb eq.] | 2,2E-2 | 7,2E-4 | 2,5E-2 | 2,1E-5 | 5,3E-5 | 6,3E-5 | 9,7E-5 | 4,1E-5 | -4,0E-3 | -1,8E-2 | 2,5E-2 |
| Abiotic Depletion (ADP fossil) [MJ] | 4,7E+5 | 1,8E+3 | 5,5E+3 | 6,3E+3 | 2,4E+4 | 9,6E+3 | 2,2E+4 | 1,4E+4 | -8,5E+2 | -4,0E+5 | 1,6E+5 |

**TABLE B.3** Numerical LCIA results for a **2-km section of Standard steel towers with concrete foundations, in mountain terrain (Scenario 1b).** Results are presented per 2-km transmission section. All methods are CML 2001 (Version January 2016). A description of impact categories can be seen in Appendix A.

| | A1-A3: STANDARD TOWERS | A1-A3: STANDARD FOUNDATIONS | A1-A3: CONDUCTOR | A1-A3: INSULATORS | A1-A3: EARTHING WIRE | A1-A3: SHIELD WIRE | A4-A5: TRANSPORT AND CONSTRUCTION | B1-B4: OPERATION AND MAINTENANCE | B1: TRANSMISSION LOSSES | C1-C4: EOL: TRANSPORT AND DISMANTLING | D: EOL: STEEL RECYCLING | D: EOL: ALUMINIUM RECYCLING | D: EOL: COPPER RECYCLING | A-D: NET IMPACTS |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Global Warming Potential (GWP 100 years), excl biogenic carbon [kg CO2 eq.] | 1,6E+5 | 7,3E+3 | 3,1E+5 | 6,4E+3 | 4,7E+2 | 1,7E+4 | 2,9E+4 | 9,9E+3 | 8,7E+5 | 1,4E+4 | -6,9E+4 | -1,5E+5 | -3,2E+2 | 1,2E+6 |
| Ozone Layer Depletion Potential (ODP, steady state) [kg R11 eq.] | 1,2E-5 | 5,7E-8 | 3,1E-6 | 2,3E-8 | 1,7E-8 | 1,4E-7 | 1,0E-8 | 6,8E-9 | 3,8E-6 | 3,8E-9 | -5,1E-6 | -1,5E-6 | -1,2E-8 | 1,3E-5 |
| Acidification Potential (AP) [kg SO2 eq.] | 3,6E+2 | 1,8E+1 | 1,4E+3 | 2,2E+1 | 2,7E+0 | 7,1E+1 | 2,4E+2 | 1,6E+1 | 9,2E+2 | 4,0E+1 | -1,5E+2 | -7,6E+2 | -1,9E+0 | 2,2E+3 |
| Eutrophication Potential (EP) [kg Phosphate eq.] | 3,6E+1 | 2,0E+0 | 8,9E+1 | 3,3E+0 | 2,2E-1 | 4,8E+0 | 3,2E+1 | 3,2E+0 | 1,4E+2 | 8,3E+0 | -1,5E+1 | -4,4E+1 | -1,5E-1 | 2,6E+2 |
| Photochem. Ozone Creation Potentia (POCP) [kg Ethene eq.] | 5,9E+1 | 2,1E+0 | 8,9E+1 | 1,5E+0 | 1,8E-1 | 5,9E+0 | 1,6E+1 | 2,9E+0 | 8,8E+1 | 3,7E+0 | -2,6E+1 | -4,2E+1 | -1,2E-1 | 2,0E+2 |
| Abiotic Depletion (ADP elements) [kg Sb eq.] | 1,6E+1 | 1,9E-1 | 6,3E-1 | 2,2E-1 | 1,1E+0 | 1,5E-1 | 1,2E-3 | 5,8E-4 | 3,3E+0 | 5,1E-4 | -3,3E-1 | -7,6E-2 | -7,3E-1 | 2,1E+1 |
| Abiotic Depletion (ADP fossil) [MJ] | 1,7E+6 | 5,6E+4 | 3,6E+6 | 6,6E+4 | 5,9E+3 | 1,8E+5 | 3,9E+5 | 1,3E+5 | 6,5E+6 | 2,0E+5 | -6,9E+5 | -1,6E+6 | -4,1E+3 | 1,0E+7 |

**TABLE B.4** Numerical LCIA results for a **2-km section of Aluminium towers with concrete foundations, in mountain terrain (Scenario 1b).** Results are presented per 2-km transmission section. All methods are CML 2001 (Version January 2016). A description of impact categories can be seen in Appendix A.

| | A1-A3: ALUMINIUM TOWER | A1-A3: ALUMINIUM TOWER FOUNDATIONS | A1-A3: STANDARD TENSION TOWER | A1-A3: STANDARD TENSION TOWER FOUNDATIONS | A1-A3: CONDUCTOR | A1-A3: INSULATORS | A1-A3: EARTHING WIRE | A1-A3: SHIELD WIRE | A4-A5: TRANSPORT AND CONSTRUCTION | B1-B4: OPERATION AND MAINTENANCE | B1: TRANSMISSION LOSSES | C1-C4: EOL: TRANSPORT AND DISMANTLING | D: EOL: STEEL RECYCLING | D: EOL: ALUMINIUM RECYCLING | D: EOL: COPPER RECYCLING | A-D: NET IMPACTS |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Global Warming Potential (GWP 100 years), excl biogenic carbon [kg CO2 eq.] | 2,2E+5 | 4,7E+3 | 4,7E+4 | 2,6E+3 | 3,1E+5 | 6,4E+3 | 4,7E+2 | 1,7E+4 | 2,3E+4 | 9,9E+3 | 8,7E+5 | 9,3E+3 | -2,5E+4 | -3,4E+5 | -3,2E+2 | 1,2E+6 |
| Ozone Layer Depletion Potential (ODP, steady state) [kg R11 eq.] | 2,5E-6 | 3,7E-8 | 3,5E-6 | 2,0E-8 | 3,1E-6 | 2,3E-8 | 1,7E-8 | 1,4E-7 | 8,3E-9 | 6,8E-9 | 3,8E-6 | 2,7E-9 | -1,5E-6 | -3,3E-6 | -1,2E-8 | 8,3E-6 |
| Acidification Potential (AP) [kg SO2 eq.] | 1,1E+3 | 1,2E+1 | 1,0E+2 | 6,3E+0 | 1,4E+3 | 2,2E+1 | 2,7E+0 | 7,1E+1 | 1,6E+2 | 1,6E+1 | 9,2E+2 | 2,6E+1 | -6,4E+1 | -1,7E+3 | -1,9E+0 | 2,1E+3 |
| Eutrophication Potential (EP) [kg Phosphate eq.] | 6,2E+1 | 1,3E+0 | 1,0E+1 | 7,3E-1 | 8,9E+1 | 3,3E+0 | 2,2E-1 | 4,8E+0 | 2,3E+1 | 3,2E+0 | 1,4E+2 | 5,5E+0 | -5,8E+0 | -9,7E+1 | -1,5E-1 | 2,4E+2 |
| Photochem. Ozone Creation Potentia (POCP) [kg Ethene eq.] | 5,9E+1 | 1,4E+0 | 1,7E+1 | 7,3E-1 | 8,9E+1 | 1,5E+0 | 1,8E-1 | 5,9E+0 | 1,1E+1 | 2,9E+0 | 8,8E+1 | 2,4E+0 | -8,8E+0 | -9,3E+1 | -1,2E-1 | 1,8E+2 |
| Abiotic Depletion (ADP elements) [kg Sb eq.] | 1,1E-1 | 1,3E-1 | 4,6E+0 | 6,4E-2 | 6,3E-1 | 2,2E-1 | 1,1E+0 | 1,5E-1 | 1,0E-3 | 5,8E-4 | 3,3E+0 | 3,5E-4 | -3,4E-1 | -1,7E-1 | -7,3E-1 | 9,0E+0 |
| Abiotic Depletion (ADP fossil) [MJ] | 2,4E+6 | 3,6E+4 | 4,9E+5 | 2,0E+4 | 3,6E+6 | 6,6E+4 | 5,9E+3 | 1,8E+5 | 3,1E+5 | 1,3E+5 | 6,5E+6 | 1,3E+5 | -2,5E+5 | -3,6E+6 | -4,1E+3 | 9,9E+6 |

**TABLE B.5** Numerical LCIA results for **Standard steel towers with steel foundations, in flat terrain (Scenario 2a).** Results are presented per transmission tower (suspension tower). All methods are CML 2001 (Version January 2016). A description of impact categories can be seen in Appendix A.

| | A1-A3: STANDARD TOWER: MANUFACTURING | A1-A3: STANDARD TOWER: GALVANIZATION | A1-A3: PREFABRICATED STEEL FOUNDATIONS | A4: CONSTRUCTION: TRANSPORT OF TOWER | A4-A5: CONSTRUCTION: HELICOPTER | A4: CONSTRUCTION: TRACKED VEHICLE | A5: CONSTRUCTION: MACHINERY USE | B1-B4: OPERATION AND MAINTENANCE | C1-C4: EOL: TRANSPORT AND DISMANTLING | D: EOL: STEEL RECYCLING | A-D: NET IMPACTS |
|---|---|---|---|---|---|---|---|---|---|---|---|
| Global Warming Potential (GWP 100 years), excl biogenic carbon [kg CO2 eq.] | 1,9E+4 | 2,7E+3 | 1,5E+4 | 1,0E+3 | 1,6E+3 | 1,6E+2 | 2,3E+3 | 1,6E+3 | 1,8E+3 | -8,4E+3 | 3,7E+4 |
| Ozone Layer Depletion Potential (ODP, steady state) [kg R11 eq.] | 1,5E-6 | 1,9E-7 | 1,2E-6 | 4,0E-10 | 3,4E-10 | 1,2E-10 | 1,7E-9 | 1,1E-9 | 4,8E-10 | -6,7E-7 | 2,2E-6 |
| Acidification Potential (AP) [kg SO2 eq.] | 3,9E+1 | 9,5E+0 | 3,2E+1 | 2,4E+1 | 4,4E+0 | 5,5E-1 | 7,9E+0 | 2,7E+0 | 5,0E+0 | -1,7E+1 | 1,1E+2 |
| Eutrophication Potential (EP) [kg Phosphate eq.] | 4,1E+0 | 7,4E-1 | 3,2E+0 | 2,5E+0 | 9,0E-1 | 1,3E-1 | 1,9E+0 | 5,3E-1 | 1,0E+0 | -1,8E+0 | 1,3E+1 |
| Photochem. Ozone Creation Potentia (POCP) [kg Ethene eq.] | 7,2E+0 | 6,6E-1 | 5,6E+0 | 1,3E+0 | 4,0E-1 | 5,4E-2 | 7,8E-1 | 4,9E-1 | 4,5E-1 | -3,3E+0 | 1,4E+1 |
| Abiotic Depletion (ADP elements) [kg Sb eq.] | 3,2E-3 | 2,2E+0 | 1,2E+0 | 4,3E-5 | 4,8E-5 | 1,4E-5 | 1,9E-4 | 9,7E-5 | 6,3E-5 | -1,4E-3 | 3,4E+0 |
| Abiotic Depletion (ADP fossil) [MJ] | 1,9E+5 | 3,6E+4 | 1,5E+5 | 1,3E+4 | 2,2E+4 | 2,0E+3 | 2,9E+4 | 2,2E+4 | 2,4E+4 | -8,3E+4 | 4,1E+5 |

**TABLE B.6** Numerical LCIA results for **guyed M-towers with steel foundations, in flat terrain (Scenario 2a).** Results are presented per transmission tower (suspension tower). All methods are CML 2001 (Version January 2016). A description of impact categories can be seen in Appendix A.

| | A1-A3: M-TOWER: MANUFACTURING | A1-A3: M-TOWER: GALVANIZATION | A1-A3: PREFABRICATED STEEL FOUNDATIONS | A4: CONSTRUCTION: TRANSPORT OF TOWER | A4-A5: CONSTRUCTION: TRACKED VEHICLE | A5: CONSTRUCTION: MACHINERY USE | B1-B4: OPERATION AND MAINTENANCE | C1-C4: EOL: TRANSPORT AND DISMANTLING | D: EOL: STEEL RECYCLING | A-D: NET IMPACTS |
|---|---|---|---|---|---|---|---|---|---|---|
| Global Warming Potential (GWP 100 years), excl biogenic carbon [kg CO2 eq.] | 1,3E+4 | 1,7E+3 | 4,9E+3 | 7,3E+2 | 3,1E+2 | 2,3E+3 | 1,6E+3 | 4,8E+2 | -6,0E+3 | 1,9E+4 |
| Ozone Layer Depletion Potential (ODP, steady state) [kg R11 eq.] | 1,0E-6 | 1,2E-7 | 4,0E-7 | 2,9E-10 | 2,4E-10 | 1,7E-9 | 1,1E-9 | 3,7E-10 | -4,8E-7 | 1,1E-6 |
| Acidification Potential (AP) [kg SO2 eq.] | 2,7E+1 | 6,0E+0 | 1,0E+1 | 1,7E+1 | 1,1E+0 | 7,9E+0 | 2,7E+0 | 1,7E+0 | -1,2E+1 | 6,2E+1 |
| Eutrophication Potential (EP) [kg Phosphate eq.] | 2,8E+0 | 4,7E-1 | 1,1E+0 | 1,8E+0 | 2,6E-1 | 1,9E+0 | 5,3E-1 | 3,9E-1 | -1,3E+0 | 7,9E+0 |
| Photochem. Ozone Creation Potentia (POCP) [kg Ethene eq.] | 5,0E+0 | 4,2E-1 | 1,9E+0 | 9,3E-1 | 1,1E-1 | 7,8E-1 | 4,9E-1 | 1,6E-1 | -2,3E+0 | 7,4E+0 |
| Abiotic Depletion (ADP elements) [kg Sb eq.] | 6,5E-2 | 1,4E+0 | 3,9E-1 | 3,1E-5 | 2,7E-5 | 1,9E-4 | 9,7E-5 | 4,1E-5 | -9,9E-4 | 1,9E+0 |
| Abiotic Depletion (ADP fossil) [MJ] | 1,3E+5 | 2,3E+4 | 4,8E+4 | 9,2E+3 | 4,1E+3 | 2,9E+4 | 2,2E+4 | 6,3E+3 | -5,9E+4 | 2,2E+5 |

**TABLE B.7** Numerical LCIA results for a **2-km section of Standard steel towers with steel foundations, in flat terrain (Scenario 2b).** Results are presented per 2-km transmission section. All methods are CML 2001 (Version January 2016). A description of impact categories can be seen in Appendix A.

| | A1-A3: STANDARD TOWERS | A1-A3: STEEL FOUNDATIONS | A1-A3: STANDARD FM TOWER | A1-A3: STANDARD FM FOUNDATIONS | A1-A3: CONDUCTOR | A1-A3: INSULATORS | A1-A3: EARTHING WIRE | A1-A3: SHIELD WIRE | A4-A5: TRANSPORT AND CONSTRUCTION | B1-B4: OPERATION AND MAINTENANCE | B1: TRANSMISSION LOSSES | C1-C4: EOL: TRANSPORT AND DISMANTLING | D: EOL: STEEL RECYCLING | D: EOL: ALUMINIUM RECYCLING | D: EOL: COPPER RECYCLING | A-D: NET IMPACTS |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Global Warming Potential (GWP 100 years), excl biogenic carbon [kg CO2 eq.] | 1,6E+5 | 1,1E+5 | 0,0E+0 | 0,0E+0 | 2,6E+5 | 6,4E+3 | 4,7E+2 | 1,7E+4 | 3,2E+4 | 9,9E+3 | 8,7E+5 | 1,3E+4 | -6,6E+4 | -1,4E+5 | -3,2E+2 | 1,3E+6 |
| Ozone Layer Depletion Potential (ODP, steady state) [kg R11 eq.] | 1,2E-5 | 9,0E-6 | 0,0E+0 | 0,0E+0 | 2,6E-6 | 2,3E-8 | 1,7E-8 | 1,4E-7 | 1,6E-8 | 6,8E-9 | 3,8E-6 | 3,5E-9 | -4,9E-6 | -1,3E-6 | -1,2E-8 | 2,1E-5 |
| Acidification Potential (AP) [kg SO2 eq.] | 3,4E+2 | 2,3E+2 | 0,0E+0 | 0,0E+0 | 1,2E+3 | 2,2E+1 | 2,7E+0 | 7,1E+1 | 2,5E+2 | 1,6E+1 | 9,2E+2 | 3,6E+1 | -1,4E+2 | -6,8E+2 | -1,9E+0 | 2,3E+3 |
| Eutrophication Potential (EP) [kg Phosphate eq.] | 3,5E+1 | 2,4E+1 | 0,0E+0 | 0,0E+0 | 7,5E+1 | 3,3E+0 | 2,2E-1 | 4,8E+0 | 3,6E+1 | 3,2E+0 | 1,4E+2 | 7,4E+0 | -1,4E+1 | -3,9E+1 | -1,5E-1 | 2,8E+2 |
| Photochem. Ozone Creation Potentia (POCP) [kg Ethene eq.] | 5,6E+1 | 4,2E+1 | 0,0E+0 | 0,0E+0 | 7,5E+1 | 1,5E+0 | 1,8E-1 | 5,9E+0 | 1,7E+1 | 2,9E+0 | 8,8E+1 | 3,3E+0 | -2,5E+1 | -3,8E+1 | -1,2E-1 | 2,3E+2 |
| Abiotic Depletion (ADP elements) [kg Sb eq.] | 1,6E+1 | 8,8E+0 | 0,0E+0 | 0,0E+0 | 5,3E-1 | 2,2E-1 | 1,1E+0 | 1,5E-1 | 1,8E-3 | 5,8E-4 | 3,3E+0 | 4,6E-4 | -3,0E-1 | -6,8E-2 | -7,3E-1 | 2,9E+1 |
| Abiotic Depletion (ADP fossil) [MJ] | 1,6E+6 | 1,1E+6 | 0,0E+0 | 0,0E+0 | 3,0E+6 | 6,6E+4 | 5,9E+3 | 1,8E+5 | 4,2E+5 | 1,3E+5 | 6,5E+6 | 1,8E+5 | -6,5E+5 | -1,5E+6 | -4,1E+3 | 1,1E+7 |

**TABLE B.8** Numerical LCIA results for a **2-km section of guyed M-towers with steel foundations, in flat terrain (Scenario 2b).** Results are presented per 2-km transmission section. All methods are CML 2001 (Version January 2016). A description of impact categories can be seen in Appendix A.

| | A1-A3: M TOWERS | A1-A3: M-TOWER STEEL FOUNDATIONS | A1-A3: STANDARD TENSION TOWER | A1-A3: STANDARD TENSION TOWER FOUNDATIONS | A1-A3: CONDUCTOR | A1-A3: INSULATORS | A1-A3: EARTHING WIRE | A1-A3: SHIELD WIRE | A4-A5: TRANSPORT AND CONSTRUCTION | B1-B4: OPERATION AND MAINTENANCE | B1: TRANSMISSION LOSSES | C1-C4: EOL: TRANSPORT AND DISMANTLING | D: EOL: STEEL RECYCLING | D: EOL: ALUMINIUM RECYCLING | D: EOL: COPPER RECYCLING | A-D: NET IMPACTS |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Global Warming Potential (GWP 100 years), excl biogenic carbon [kg CO2 eq.] | 7,5E+4 | 2,4E+4 | 4,7E+4 | 3,6E+4 | 2,6E+5 | 6,4E+3 | 4,7E+2 | 1,7E+4 | 2,3E+4 | 9,9E+3 | 8,7E+5 | 6,3E+3 | -5,3E+4 | -1,4E+5 | -3,2E+2 | 1,2E+6 |
| Ozone Layer Depletion Potential (ODP, steady state) [kg R11 eq.] | 5,8E-6 | 2,0E-6 | 3,5E-6 | 2,9E-6 | 2,6E-6 | 2,3E-8 | 1,7E-8 | 1,4E-7 | 1,4E-8 | 6,8E-9 | 3,8E-6 | 2,9E-9 | -3,9E-6 | -1,3E-6 | -1,2E-8 | 1,6E-5 |
| Acidification Potential (AP) [kg SO2 eq.] | 1,7E+2 | 5,2E+1 | 1,0E+2 | 7,6E+1 | 1,2E+3 | 2,2E+1 | 2,7E+0 | 7,1E+1 | 2,0E+2 | 1,6E+1 | 9,2E+2 | 1,9E+1 | -1,2E+2 | -6,8E+2 | -1,9E+0 | 2,0E+3 |
| Eutrophication Potential (EP) [kg Phosphate eq.] | 1,6E+1 | 5,3E+0 | 1,0E+1 | 7,8E+0 | 7,5E+1 | 3,3E+0 | 2,2E-1 | 4,8E+0 | 2,8E+1 | 3,2E+0 | 1,4E+2 | 4,3E+0 | -1,2E+1 | -3,9E+1 | -1,5E-1 | 2,5E+2 |
| Photochem. Ozone Creation Potentia (POCP) [kg Ethene eq.] | 2,7E+1 | 9,2E+0 | 1,7E+1 | 1,4E+1 | 7,5E+1 | 1,5E+0 | 1,8E-1 | 5,9E+0 | 1,3E+1 | 2,9E+0 | 8,8E+1 | 1,8E+0 | -2,0E+1 | -3,8E+1 | -1,2E-1 | 2,0E+2 |
| Abiotic Depletion (ADP elements) [kg Sb eq.] | 7,3E+0 | 2,0E+0 | 4,6E+0 | 2,9E+0 | 5,3E-1 | 2,2E-1 | 1,1E+0 | 1,5E-1 | 1,6E-3 | 5,8E-4 | 3,3E+0 | 3,5E-4 | -3,0E-1 | -6,8E-2 | -7,3E-1 | 2,1E+1 |
| Abiotic Depletion (ADP fossil) [MJ] | 7,8E+5 | 2,4E+5 | 4,9E+5 | 3,6E+5 | 3,0E+6 | 6,6E+4 | 5,9E+3 | 1,8E+5 | 3,0E+5 | 1,3E+5 | 6,5E+6 | 8,5E+4 | -5,3E+5 | -1,5E+6 | -4,1E+3 | 1,0E+7 |