Published at IASTED EuroPES 2007, Palma de Mallorca, Spain

DESIGN AND CONSTRUCTION OF A 4 KW GROUNDSTATION FOR THE LADDERMILL

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ABSTRACT
This paper presents the design of a 4 kW Laddermill groundstation. The Laddermill is a novel concept to harvest electricity from high altitude winds. The concept's operating principle is to drive a generator with kites. Several kites are high in the air at an altitude of more than 1 km. All kites are connected to a single cable that connects to a drum in the groundstation. The lower part of the cable is connected to the kites and is wound around a drum. The kites pull the rope from the drum, which in turn drives a generator. When all of the cable is pulled off the drum, the kites fly down in a configuration that generates significantly less lift than during the ascent. This way the lower part of the tether is retrieved onto the drum and the process is repeated. The concept allows very large single unit power. At Delft University of Technology, a 2 kW test model of the Laddermill was constructed and tested successfully. From this 2 kW Laddermill several valuable lessons were learned. Taking the lessons learnt into account, a 4 kW groundstation was designed.

KEY WORDS
Kites, Energy, High altitude, Ground station.

1. Introduction

Energy is an important asset in modern society. Most energy is generated from non-renewable recourses such as coal, gas oil and uranium. In recent years the push for renewable energy has increased, resulting in rules that regulate the amount of renewable energy a country should produce. Among the possibilities of renewable energy are solar, hydroelectricity, wind, and biomass energy sources. Unfortunately, these technologies can only supply small amounts of energy per installed unit. The Laddermill aims to produce a quantum leap in "environmentally clean" electricity generation by utilising the vast amount of energy available in high-altitude winds.

Wind energy has been used for several hundreds of years, and Holland is famous for its windmills used for mechanically powering pumps and equipment. The current windmill design arose from the Hallady-Perry windmill design of the 1920s and 1930s. Since then large steps have been made in power output and efficiency. Modern wind turbines are placed well above the ground at altitudes up to 120 m due to the fact that both wind speed and steadiness increase significantly with altitude. The power generated by wind turbines does not merely increase linearly with wind speed, but rather by the cube of the wind velocity. Hence, doubling the wind speed increases the available power by eight times. It is this fact that has lead many researchers to propose various concepts for extracting electricity from higher altitudes. Figure 1 shows the average wind over 20 years in the Netherlands versus the altitude.

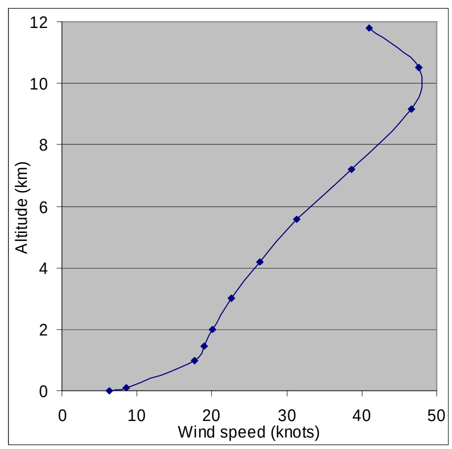

Figure 1: Average windspeed over the Netherlands versus the altitude[1],[2]

The idea of using airborne windmills for electricity generation was investigated in multiple occasions[3]-[11]. All abovementioned systems feature a generator that is high up in the air. This means that a large payload and a conductive tether must be supported, adding to the weight and cost of the system, while the forces necessary to lift the apparatus do not provide power. An alternative concept was proposed by Ockels[1],[12], called the Laddermill, where power is generated by wings or kites that drive an electric generator by means of the cable.

2. The Laddermill

The Laddermill concept makes use of lifting bodies, called kites or wings, connected to a cable that stretches into the higher regions of the atmosphere. The lower part of the cable, about 10% of the total length is wound around a drum. The tension that the kite creates in the cable pulls it off the drum, thus driving the generator, as shown in Figure 2.

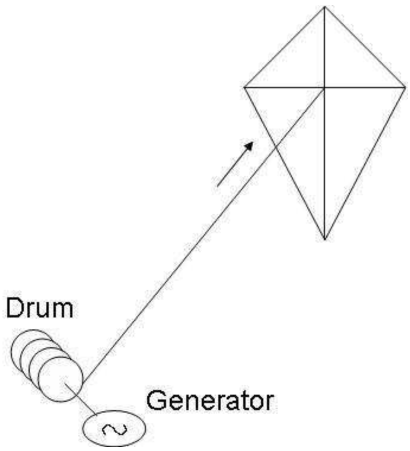

Figure 2: Simple illustration of the Laddermill principle

When the kite is ascending the attitude of the kite is such that it generates high lift. This can be done by increasing the apparent wind by using crosswind power [13] and/or by increasing the angle of attack.

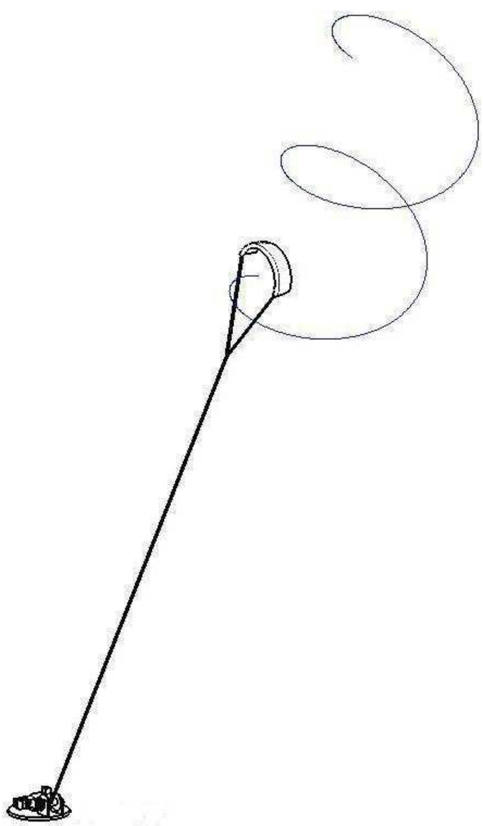

Figure 3: Kite ascending

Once the cable has been pulled of the drum, the cable must be retrieved. In order to generate a surplus of energy the lift of the kite has to be reduced. This can be achieved by refraining from using crosswind power and by lowering the angle of attack. A high ratio between the cable tension when ascending and the cable tension when descending will increase the power output and efficiency of the Laddermill. Only the lower ~10% of the cable will be retrieved. The rest of the cable with the wings attached will always remain airborne during normal operation. In case of windless conditions the whole Laddermill will be retrieved. Preliminary simulations show this will occur about 40 times per year. Modeling and simulations of the Laddermill system are performed to determine the optimal values for reeling length, optimal path for energy extraction and system performance[14]-[19].

The actual Laddermill will have several wings connected in the upper section of the cable. An artist impression of the Laddermill is shown in Figure 4.

Figure 4: Artist impression of the Laddermill

The installed power of a Laddermill can be higher than that of conventional windmills. Since the wings are high up in the air, their size is not limited like the blades of a conventional windmill. Large controllable kites are thus an enabling technology for the Laddermill. Preliminary results with remotely controllable kites exist [20]. Measurements and modeling of kites is an important part of the research [21]-[23]. Higher installed power will lead to a larger cable diameter and a larger, ground-based, generator. Larger single-unit outputs are expected to decrease the cost per kWh.

3. Groundstation requirements

The 4 kW groundstation was designed bearing in mind the experiences with the 2 kW groundstation that was built in 2004. The lessons learnt from the previous model will be explained briefly. A paper on the previous design can be read for further information on the 2 kW groundstation[24].

3.1. 2 kW lessons learnt

The 2 kW groundstation is shown in Figure 5. It features a stationary drum with a traversing mechanism on top to nicely reel the cable. The drum is about 15 cm in diameter and 40 cm wide.

Figure 5: 2 kW groundstation

The main lessons learnt from this design are:
1) Storing the cable on a layer wound drum will damage the cable because of cutting.
2) The layer wound drum will result in microslip occurring between the top layer of cable and the one below. The cable stretches over a certain length while it is still on the drum, as presented in Figure 6, where α is the angle over which the slip occurs. For Dyneema with a large difference between N^+ and N^-, the angle will be more than a full revolution.

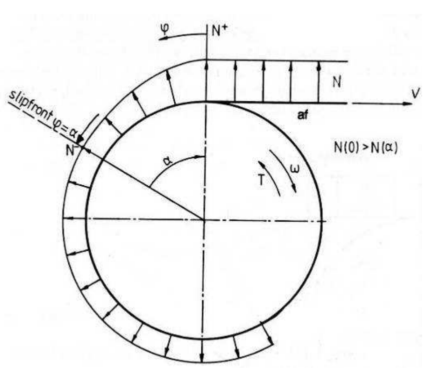

Figure 6: Microslip because of alternating stress

3) Normal slip occurs when the kite flies in geometric patterns. During retraction the traversing mechanism keeps the cable straight above the drum, shown in Figure 7.

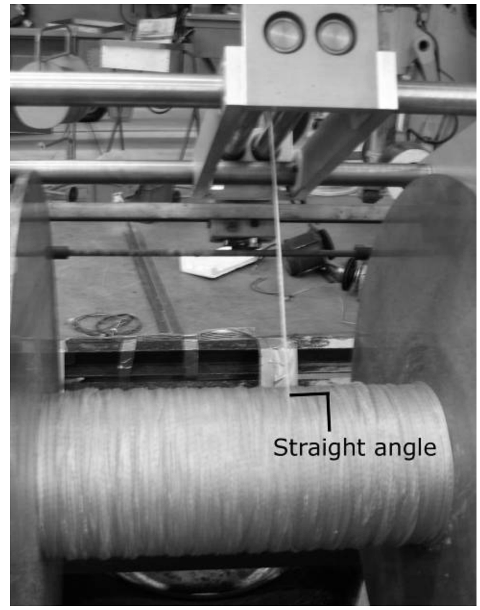

Figure 7: Cable leaving the drum - straight angle

The traversing mechanism is not strong enough to deal with the sideways pointing force in the cable. Therefore, it is decoupled during the power generation phase, causing the cable to leave the drum under a different than straight angle, shown in Figure 8

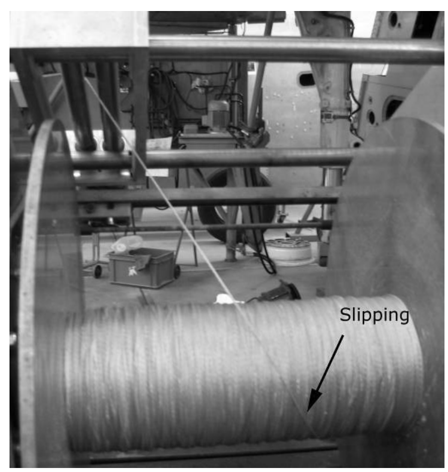

Figure 8: Cable leaving the drum - wrong angle

Taking these lessons learnt into account the requirements for the 4 kW groundstation could be formulated.

3.2. Requirements

The requirements are formulated taking into account that the design should be scaled up to much larger dimensions in the future for larger Laddermills. This means a minimum number of rolls deforming the cable because these rolls require very large diameters for thicker cables. Only the most important requirements, influencing the operating principle of the Laddermill groundstation will be discussed. Figure 9 shows the definition of the cable angles.

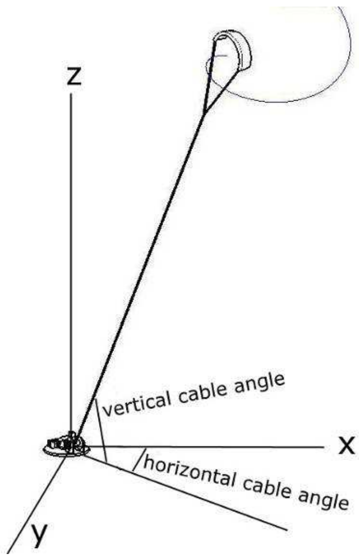

Figure 9: Cable angles

- The groundstation should allow a large range of vertical cable angles, about 0-120 degrees
- The groundstation should allow 360 degrees of horizontal cable angles to allow geometric pattern flying and changing wind directions
- The groundstation must feature a capstan type drum and enable winding on the drum

3.3. Analogies in existing machinery

The capstan type drum is used frequently in mooring line installation when polymer cables are used. A 12 m diameter drum with a 30 cm thick cable is shown in Figure 10.

Figure 10: Capstan drum on a ship of Heerema.

4. Conceptual solutions

Reeling of highly loaded cables is commonly done by a capstan winch, as presented in Figure 11.

Figure 11: Capstan winch

This design could be applied for the Laddermill, having the capstan winch drive the generator and afterwards storing the low-tension cable on a separate drum. The diameter of the capstan is determined by the diameter of the cable; it needs to be about 20 times thicker than the cable. For a large Laddermill with a 0.1m diameter cable, this results in a capstan diameter of 2 m. In a single revolution around the capstan, about 6 m of cable is stored. To reduce the tension in Dyneema about 10 revolutions around the capstan are required. 60 m of cable are therefore stored on the capstan. It was decided that it would be more efficient to store all the cable on the capstan, which results in a drum that looks like the capstan drum in Figure 10.

4.1. Vertical cable angle

Two options were considered for the vertical cable angle.

1) Horizontal axis cable guide

2) Using the drum itself; since the drum is (probably) a horizontal axis cable guide, it can be used as such.

4.2. Horizontal cable angle

Three concepts were considered to deal with the horizontal cable angle caused by different wind angles and geometric pattern flying.

1) Mount drum on rotating platform

2) Guide cable through a rotating guide (like the on in Figure 12) on top of drum.

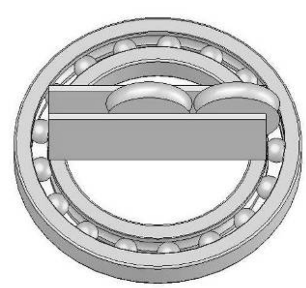

Figure 12: Rotating guide

The cable comes through the center of the bearing and between the two pulleys. The opening between the pulleys is off center, such that the cable force will always rotate the outer pulley into the cable direction.

The second pulley keeps the cable in its place when the cable is retracted and the vertical cable angle is larger than 90 degrees.
The cable must move through the center of the bearing because otherwise it will not allow 360 degrees of freedom in rotation.
3) Two sets of horizontal axis cable guides, shown in Figure 13. This concept also deals with the vertical cable angle, although the vertical cable angle will have to remain higher than about 30 degrees.

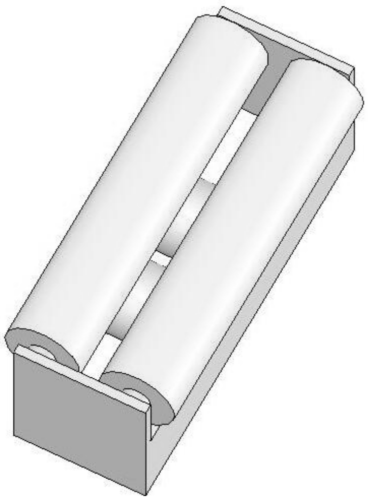

Figure 13: Two sets of horizontal axis cable guides

This concept will result in wear in the cable because the cable will slip over the top cable guide. Also, all four guides will be heavily loaded, requiring a total of eight large bearings. This concept will not be considered in the trade-off.

4.3. Cable winding

Three concepts were considered for winding:
1) A traversing mechanism that traverses the cable over the drum. The traversing mechanism must be strong enough to deal with the forces caused by geometric pattern flying.
This concept will no longer be considered because the force required moving the traversing mechanism is much larger than the force required to move the drum.
2) A traversing mechanism that traverses the drum, possibly under a fixed cable guidance. This traversing mechanism must move the mass of the drum and all part connected directly to it, but is not affected by the tension in the cable.

4.4. Tradeoff

Only two possible combinations of concepts remain. The first is a traversing drum mounted on a rotating platform, with a vertical axis cable guide for stability, shown in Figure 14.

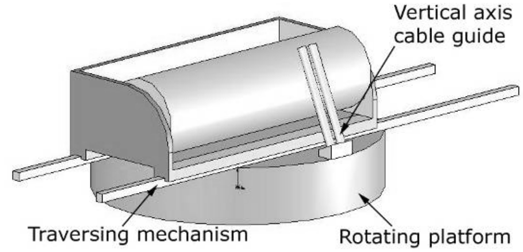

Figure 14: Rotating platform concept

The second is a traversing drum under a rotating horizontal axis cable guide, with a vertical axis cable guide for stability, shown in Figure 15.

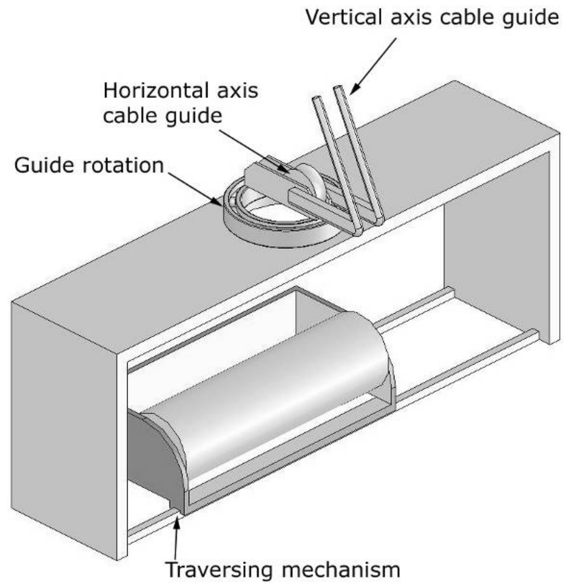

Figure 15: Rotating guide concept

The differences between the two concepts are limited. Both feature a vertical axis cable guide that is only required to auto-rotate into the cable direction. The forces on it are negligible and it could even be replaced by a motorised rotation that actuates the drum or the pulley in the cable direction. Both concepts feature an identical traversing mechanism. The rotating platform and the guide rotation are not unalike: the forces on them are of the same order of magnitude. The rotating guide concept has a horizontal axis cable guide that is not present on the rotating platform concept. Since the horizontal axis cable guide is heavily loaded, this is a disadvantage. The horizontal axis cable guide also results in an additional deformation of the cable (the first deformation being caused by the drum in both concepts).
A disadvantage of the rotating platform concept is that the whole structure rotates, while in the rotating cable guide concept only the cable guide rotates. On the other hand, the launch mechanism may be installed on the rotating platform, such that it will also rotate into the wind.

At this stage in the research, it is considered unwise to make a selection between the two concepts. Therefore, a single machine will be designed that can test both.

5. Construction

The groundstation consists of a number of subsystems that will be explained briefly. After that the two concepts, the rotating platform concepts and the rotating cable guide concept will be explained.

5.1. Subsystems

Drum: The drum is a large, aluminium cylinder with a diameter of 0.3 meter and a length of 1 meter. The cable is wound onto it in a single layer. This avoids cutting of the cable in underlying layers. Figure 16 shows the drum with the cable on it, installed on the traversing train.

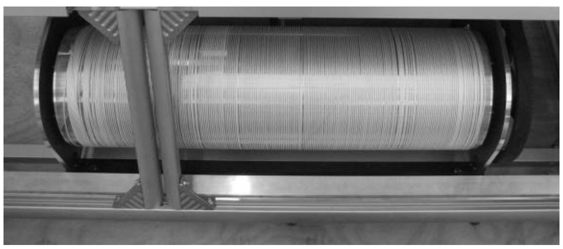

Figure 16: Drum

Traversing mechanism: the traversing mechanism drives the drum under the cable guide. The rotation of the drum drives this motion. It is transferred to a linear motion by means of a lead screw, as shown in Figure 17.

Figure 17: Lead screw + nut

The lead screw is connected to the traversing train, the nut is connected to the ground.
The drum moves on a guidance, consisting of six cylindrical bearings. Four bearings take the vertical loads while the other two take the horizontal loads. The guiding system is shown in Figure 18.

Figure 18: Guiding rails & wheels

Electrical system: the electrical system consists of two 12 V batteries, a motor controller, and a 24 V DC motor. The motor controller is operated by a laptop through an interface box. Currently, two sensors are available for control purposes: a shunt resistance is used to measure the current to determine the power output of the motor and tachometer is used to determine the cable speed. In early stages, the motor will be controlled to a certain RPM. After that a power point tracker will be programmed.
Brake system: The brake is used for emergencies and when the cable speed is naught. It is shown in Figure 19.

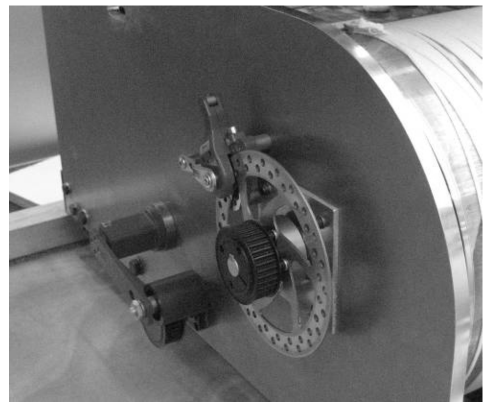

Figure 19: Brake

Gearing: The gear consists of two tooth belt pulleys with a 1:6 ratio, shown in Figure 20. In the background the motor can be seen.

Figure 20: Gear + motor

5.2. Rotating platform concept

For the rotating platform concept, a rotating platform was designed. It is shown in Figure 21.

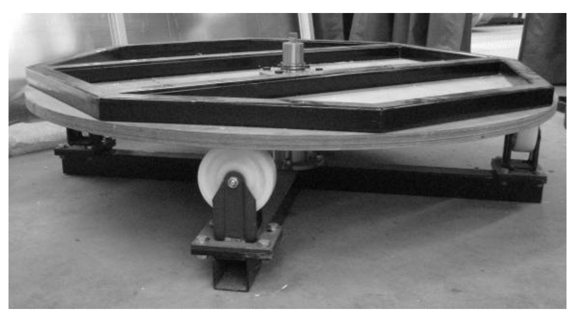

Figure 21: Rotating platform

The platform can take loads up to 5000 N in any radial direction and also 5000 N in positive and negative axial

direction. This is necessary because the lift of the kite could otherwise lift the rotating plate off the wheels.
Figure 22 shows the groundstation on the rotating platform.

Figure 22: Groundstation on rotating platform

It was found that the inertia of the groundstation makes it hard for the tension in the line to auto-rotate the groundstation into the right direction. For this reason, the rotation of the platform has to be enforced by measuring the line angle and rotating the groundstation by means of a motor to get the angle straight. Since this will require a sensor and a motor, the rotating cable guide concept will be tested first.

5.3. Rotating cable guide concept

For the rotating cable guide concept, a mechanism was designed that can freely rotate and sustain radial loads up to 20 kN and axial loads of 20 kN. It can be used for a Laddermill groundstation of up to 50 kW. It is shown in Figure 23

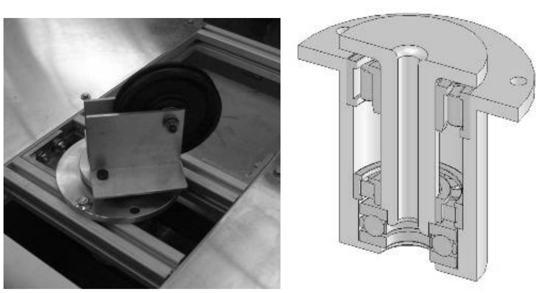

Figure 23: Rotating cable guide

5.4. Groundstation on VW Crafter

As mentioned, the rotating cable guide concept will be tested first. Figure 24 shows the groundstation with the rotating cable guide on the Volkswagen Crafter pickup van. The van will be used to transport the groundstation to a suitable test location.

Figure 24: Groundstation on the Volkswagen Crafter pickup van

6. Sensors & electronics

The groundstation is operated by a laptop computer. A number of sensors and actuator are installed.
Sensors: two sensors are installed on the groundstation: a hall sensor measures the rate of rotation and a shunt resistor is used to determine the power (because the voltage is constant). The integrated rate of rotation can be used to determine how much line is on the drum.
Actuators: The motor controller uses a digital potentiometer to control the rate of rotation of the motor. Via the computer, the rate of rotation can by controlled. The rate of rotation can be changed by operator, using a joystick. Another option is to give the computer a fixed speed, but a power point tracker is also installed. The brake can be actuated by the computer when the drum should not rotate.

7. Discussion and conclusion

Testing of the 4 kW groundstation will yield useful information on several issues including:

- Pre-tensioning: is pre-tensioning required for good winding? Is there a large risk for slack tether?
- Automated rotation vs. auto rotation: is it possible to loose the vertical axis cable guide by actively driving the rotation of the platform/guide
- Cable wear: how does Dyneema withstand microslip

Information on these issues will result in an improved design for the next Laddermill groundstation.

8. Acknowledgements

The Laddermill project is sponsored by: Shell research, Fugro, Gasunie, University of Groningen, Delft University of Technology, the province of Groningen, the county of Groningen and the county of Delft.

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