The Alchemists: turning wild water into white coal

It's an hour before midnight on February 27, 1943, and nine Norwegian men — saboteurs — are slipping and sliding down a snow-covered, steep walled gorge in Rjukan, Norway. Below them, the giant Vemork hydroelectric plant bristles with Nazi guards.

The Vemork power plant is the largest in the world. It opened in 1911, and the cost of building was more than the Norwegian national budget. Norsk Hydro needed every one of the 108 megawatts it could generate so they could make their signature product — nitrogen-based fertilizer.

But that's not what the Norwegian saboteurs are after. Their goal is in the basement of the seven-story concrete hydrolysis plant. Hydro uses the electricity from the power plant to split water molecules into hydrogen and oxygen — a process called hydrolysis. The hydrogen can then be used to extract nitrogen from the air to make fertilizer.

A by-product of this process is a substance called deuterium, or heavy water. Hydro started to collect heavy water in 1935, shortly after it was discovered, for scientific use. A chemist and professor at the university in Trondheim, Leif Tronstad, designed the Vemork system.

But in 1943, the Allies feared the Germans could use the heavy water from occupied Norway to aid their efforts to build an atomic bomb. It was enough of a worry that the Allies had *already* tried — and failed, in an effort that killed 41 British soldiers — to blow up the heavy water plant.

Just after midnight, the saboteurs cut the barbed wire and the metal fencing around the plant and enter the basement.

A Norwegian worker inside hears the men discussing their choice of fuses to blow up the heavy water system. Realizing what is afoot, he politely asks the saboteurs to allow him to get his glasses. He is worried he won't be able to replace them, given the scarcity of goods in wartime Norway. But the glasses are nowhere to be found.

Minutes tick by as the saboteurs search for the glasses. Every second risks having a German guard discovering the men with their explosives.

Finally the glasses are located. The saboteurs send the worker off to safety and light their fuses —30-second fuses as it happens — and steal away…..

I'm Nancy Bazilchuk, and you're listening to 63 Degrees North, an original podcast from NTNU, the Norwegian University of Science and Technology.

Today, I'm going to tell you the story of the scientists and engineers who turned Norway's wild waters into what they called white coal: hydropower. More specifically, I'm going explore some of the ways these alchemists have been working to wring every kilowatt of energy out of falling water.

They include an engineer who figured out how to harness national fervour and build the 1900s equivalent of a super computer, a WWII resistance fighter who saw something special in tiny temperature differences, and researchers today, who are figuring out how pumping water backwards through a hydropower plant may be the future in a zero carbon world.

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First, a little background. You may think of oil as Norway's main economic driver — and these days it is. But at the beginning of the 20th century, when Norway had just emerged as a new nation, it was hydropower that formed the underpinning of the Norwegian economy. And it was big —big enough to make the construction of the giant Vemork plant a sound economic investment — and more.

Norway's capacity to generate cheap electricity from falling water made it a magnet for energy-intensive industries — like aluminium. If you haven't heard it already, you can listen to the episode I did earlier in the season on the history of aluminum in Norway.

The realization of just how valuable Norwegian waterfalls were in the early 1900s forced the Norwegian government to enact something called the Panic Law to get things under control. Hans Otto Frøland, an NTNU historian, explains.

Hans Otto: There was one law that called the panic law because so many foreigners came to Norway to buy up waterfalls cheap, because it was poor peasants who own these waterfalls, and they didn't know the future value of it.

Nancy: Fertilizer, Norsk Hydro's main product at this time, was a perfect product for Norway to make and export, because it required enormous amounts of cheap energy to produce. So it was a product that could be manufactured with the natural resources — waterfalls — that Norway had to offer, as former Hydro CEO Svein Richard Brandtzæg explains.

Svein Richard (20:17)
Hydro built up the Rjukan plant just a few years after the company was established, the company financed the expansion and establishment in Rjukan with the money from Sweden and France and spent about 1.5 times the Norwegian national budget. So, it was the biggest hydropower station in the world at that time.

Nancy: Yes, this is the same place the saboteurs attacked during the Nazi occupation.

Svein Richard: And also the fertilizer production which was really something, that was enough to fulfil the target to feed a hungry world at that time, because the world needed fertilizer.

Nancy: One event that happened to help drive Norway's hydropower adventure happened right here in Trondheim, right in my backyard.

SOUND of footsteps going up metal stairs

Ole Gunnar: 134 (1:39) Right now we are in the Water Power Lab, which is an old building, it was built in 1917. But internal parts of the lab is quite new. And up to date, I would say it is state of the art. And in my opinion, the best one in the world.

Nancy: That's Ole Gunnar Dalhaug

Ole Gunnar: 1:34 (1:34) I work as a professor at the Department of Energy and Process Engineering.

Nancy: Ole Gunnar is pretty modest. He is also head of the Water Power Lab. As a matter of record, the Lab was built not that long after NTNU's predecessor, the Norwegian Institute of Technology, opened its doors in 1910.

Ole Gunnar: So, the whole building is built upon system in the basement which is consists of 450,000 litres of water, we have a pump system which can pump into the system about 1100 litres per second into the system. So yes, we can spill a lot of water here.

The big tank over there consists of 18 cubic metres of water, and you can pressurise it up to 100 metre water column. And if you look around, you see that the infrastructure is mainly built with these pipes, which are 600 millimetre in diameter.

It’s built in a style that you would expect from this era, with intricate wrought iron railings in the shape of a tree with spreading branches. It’s five stories tall, but really narrow — to my eye it looks like a giant antique carriage house.

It was built this way so it could provide the kinds of forces you’d get from a high waterfall, which allows researchers to test turbines.

Turbines are the equipment that the water flows through, and th at turn falling water into electricity. If you want to squeeze every electron possible out of falling water, you have to have an efficient turbine. Those 600 millimetre pipes Ole Gunnar mentioned — they’re big enough to crawl through, so they can release a lot of water with a lot of power. And when the water power lab is running a big experiment, you can tell with your eyes closed. It feels like the whole structure hums.

The man who was the brains behind the Water Power lab was:

Ole Gunnar 127 (11:14) Gudmund Sundby.

Nancy: Sundby was hired in 1912 by Norwegian Institute of Technology in 1912 and realized early on that what Norway needed was a laboratory where it could test turbines and improve their efficiency.

Ole Gunnar: So he started to work politically right away, and in 1917, it was up and running. And I know that they started to build it in 1915. So he only spent two years to develop it but *for a government that didn't have a lot of mone*y, it was really a huge investment.

Nancy: In today’s currency, the lab cost between 40-50 million kroner, or roughly 6 million USD. To put this in contact, that was one-tenth of one percent of the entire Norwegian national budget. It may not sound like much until you realize that the American government spent 1 percent of its national budget on the Manhattan Project to develop the atomic bomb.

Sundby came to the university from a company called Kværner Brug, a Norwegian company that got its start in 1853, at first making cast iron products, including woodstoves. They started making turbines and other equipment for hydropower production as early as 1880, and by 1900 turbines were a big focus.

So Sundby had practical experience, but he also had a secret weapon. An old buddy, Gunnar Knutsen, happened to be prime minister at the time that Sundby was hired by the university.

Knutsen knew that hydropower was the future for Norway — he himself had been involved in passing the panic laws that Hans Otto Frøland talked about, to protect

Norwegian waterfalls from being bought up by foreign investors. That definitely helped.

In addition to being well connected, Sundby had another card to play.

Ole Gunnar 127 (12:17) They saw Sweden was doing the same thing….That also was a motivation.

Nancy: Norway had only just dissolved its union with Sweden in 1905, and Norwegians still had very intense feelings about their neighbour to the east. Sundby argued that if Norway didn't invest in its ability to make turbines, Norwegian companies would have to buy turbines from Sweden. Everyone knew that hydropower was the key for Norway to enter the modern age. And no Norwegian wanted to have to depend on Sweden.

Nancy: You might wonder, what difference does a building make? Well, the huge size of the laboratory and its giant piping system allowed engineers to actually test scale models of different turbine designs and fiddle with them to make them really efficient. During this period, engineers had to make careful drawings and do all their calculations by hand. Remember that 1900s' equivalent of a super computer I mentioned in the beginning? This is it. It's not exactly a super computer because they still had to do calculations.

Ole Gunnar: 118 (7:33) Today, we have numerical tools and computers, but at that time, you had to do it by hand.

Nancy: But the Water Power lab allowed them to test their calculations in real time, by building scale models and actually subjecting them to the forces equivalent to a real Norwegian waterfall, so they could see if what they were doing was right.

Ole Gunnar: you could say something about energy in the water and energy on the turbine. And by adding those equations and looking at it, you're able to shape the blades optimum by doing that.

Nancy: The blades are the structures inside the turbine housing that the water actually strikes.

Ole Gunnar: It was an iterative process. And I know that they spent days, weeks months doing these calculations.

Nancy: Hydropower was pretty efficient, even back in this period, when a hydropower plant could capture as much as 80 percent of the energy of the falling water and turn it into electricity. To put that in context, the most efficient of today's wind turbines only turn 40 percent of the energy of the wind into electricity. By testing turbines in the waterpower lab, however, Professor Sundby and his band of engineers were able to make water turbines incredibly efficient.

Ole Gunnar: 118 (5:43) they did experiments in this building and the people in this house, especially the professor's, they developed the technology further: how to shape the blades, how to shape the geometry of the turbines.
Ole Gunnar: 118 (10:00) So they made turbines up to 93% efficiency. Today, the state of the art is 96.

Nancy: Almost immediately, the Water Power lab began delivering results that had real economic impact. The most visible project was the Mørkfoss-Solbergfoss hydropower station that was built starting in 1913 to supply Norway's capital, Oslo. Norway's two turbine suppliers, Kværner Brug and Myrhen Verkstad, were able to test their turbines at scale in the lab, which helped make them so efficient.

When it came on line in 1924, these highly efficient, Norwegian-made turbines led technology writer Georg Brochmann to exclaim "there is hardly any other academic institution in this country that has provided such rich earnings as this laboratory. Norwegian hydropower is Norway's biggest asset, and it will mean more wealth for this land if we learn how to exploit it economically than if we had discovered an extremely rich gold mine."

Nancy: Hydropower construction was hampered some during the 1930s, because of the Great Depression, but the Second World War really turned things upside down. The Germans were intent on expanding Norway's aluminium production so they could build more fighter planes. And Norwegian engineers suddenly found themselves in the position of trying to destroy the very developments they had worked so hard to create.

Nancy: Leif Trondstad is a good example. He was a chemist at the Norwegian Institute of Technology, called NTH, which was one of NTNU's main predecessors. So while he wasn't a hydropower engineer, he was the man who worked with Norsk Hydro to design the heavy water plant in Vemork. At first, he was spying on the Nazis in Norway, but things got too hot for him and he escaped to England. Once the British military realized how well he knew the Vemork plant, they asked him to figure out how to blow it up. It was he who organized the saboteurs' attack on the plant in 1943.

Then there was:

Ole Gunnar (118) 25:03 Knut Alming.

Nancy: He was a 22 year old hydropower engineering student at NTH when the war came to Norway.

Ole Gunnar:118 (25:03): He was working with the resistance in Norway.

Nancy: Long story short, he used the Water Power Lab to send information about the Nazis to the UK. The Gestapo came for him and he barely escaped with his life.

Ole Gunnar: He came back after the Second World War, and he was a professor here.

Nancy: Knut Alming actually took over as head of the Water Power lab in 1952, right as hydropower development in Norway was really taking off. Alming was a leading research on turbine efficiencies — something that would cause him and Ole Gunnar to cross paths decades later. It may seem strange, but the best way to figure out how efficient a turbine was had to do with measuring tiny differences in water temperatures.

Ole Gunnar: 118 (37:23) In the early 1950s, there was a French professor that stated that he could measure the efficiency on the turbines by measuring the temperature difference between the inlet and outlet of the turbines, stating that all losses in the turbine goes to heating the water up. So a lot of work was carried out in this lab trying to prove that.

They said that they wanted to prove it wrong, actually, and what happened was that they proved it right. And since the 1950s, that way of doing efficiency measurements on the power plant has been developed further here at at this lab.

Nancy: But here's the thing that I find kind of mind boggling. How do you accurately measure water temperatures so you can detect improvements, if there are any? Where do you put the temperature probe? You can't just dangle a little thermometer in the huge outflow from a hydropower plant. And how many temperature measurements do you actually need? Ole Gunnar did a lot of research himself on this question.

Ole Gunnar: 118 (38:36) My contribution was to see how the temperature was distributed over the outlet area of the turbine. And we're talking about the difference of 0.01 degrees Celsius over that cross sectional area, which was in this case 20 by 10 metres. It's a huge system.

39:06 we set up a frame in the outlet and we have many sensors, and the sensor has to be very sensitive. It measures one/1000th of a degree Celsius and I had 26 points where I measured the temperature.

Nancy: In fact, the first ever academic paper Ole Gunnar presented at a professional conference was on this research. And much to his horror, he found out that Knut Alming, the war hero who had been at the forefront of refining the use of temperature differences to determine turbine efficiencies, was in the audience. And he was known to be kind of a strict guy.

Ole Gunnar 118 (28:16) I was scared because I understood that if he started to work against me, then I will be in trouble. He didn't say anything during the conference. But he came to me afterwards. I was expecting him to say something was bad.

Nancy: That isn't exactly what happened.

Ole Gunnar: The first thing he asked was "Do you like whiskey?" Apparently he is a fan of scotch whiskey. So he offered me a single malt whiskey. …118 (39:32) I think Alming appreciated the work.

Nancy: The reason this matters so much — not the whiskey of course — is that even a small improvement in efficiencies in hydropower turbines can really add up. A hydropower plant is kind of like a perpetual motion machine. As long as there is water in the river or in a reservoir, it can run through the turbines all the time and generate electricity. And hydropower plants and their turbines operate for decades. If they perform 10 per cent better than a less well designed system, you're getting that 10 per cent extra payback ever second, every hour, every day the plant is operating.

Nancy: These days, roughly 90 per cent of all electricity generated in Norway comes from hydropower. Norway is the seventh largest hydropower producer in the world.

And as is true for all big public projects, hydropower development, especially in more recent years, could be controversial, because it does have environmental impacts. And part of what researchers at the Water Power Lab are studying now is how some of those impacts can be reduced.

One impact happens when there are high water flows around hydropower plants. Lots of air can get trapped in the water, so much so that

Vera: 123 (1:11) You can imagine it like a Big Soda Stream.

Nancy: That's Vera Gutle…

Vera: I'm from Germany, I'm studying at TU Berlin, and currently writing my master's thesis here at the Water Power Lab. And I'm trying to degas supersaturated water, which might occur at hydro power plants.

Nancy: The problem is that if the water around hydropower plants becomes supersaturated with air — which can happen during high flow periods, like during the spring snowmelt — it can make fish sick in the same way that divers who have been breathing pressurized air and who come up to the surface too quickly can get “the bends”, where gas bubbles form in their bloodstream. Fish can get it too.

Vera: 123 (5:20) So some power plants there are less fish in the water or even zones without any fish. And so we are trying a technical solution to degas the water, which then can be used by the hydropower plant companies, hopefully one day.

SOUNDS from the Water Power lab

Nancy: So Vera can actually simulate what it’s like downstream of a hydropower plant where the water is supersaturated with air. First they make the water.

Vera: (0:56) We have a big water tank, a pressure tank, and we can test 18,000 litre of water, we can fill it up and pressurize it, and then we introduce air in the tank.

Nancy: That’s your giant Soda Stream machine, but with air instead of CO2.

Vera: We have connected a channel to the tank. The channel has 18 metre of length, and in the beginning of the channel, we have an ultrasound transducer. So we let water from the tank run through the through the channel. And then we apply the ultrasound and measure the amount of air which is dissolved in the water. And then we are testing if we can reduce the amount of air that's in the channel.

Nancy: Then there’s the question of what Norwegian hydropower can offer, as more and more of our electricity comes from renewable sources like wind and solar power. The challenge is that

Ole Gunnar 118 (10:59), the wind doesn't blow all the time. So you need to have some kind of backing when it doesn't blow, for example. We just built the Europe's biggest wind farm on Fosen just west of Trondheim, 1000 megawatts. And in that area, it it blows quite a lot. But sometimes it doesn't blow at all. And sometimes it blows. It is a storm. So the turbine stops when the storm is coming. And of course they’re stopped when it's not blowing. So let's say that a storm is coming. And and the turbines has to shut down — 1000 megawatt is shutting down in minutes.

How do you back that up? So let's say that Hydro aluminium is the customer of the energy from that area, and they are they are smelting aluminium, they can't afford to stop the smelter, that will be disaster.

Nancy: Well, can’t you just fire up a hydropower plant? Ole Gunnar says no.

Ole Gunnar: So that flexibility is possible in hydropower plants it but they are not designed for it. So we have to develop that technology further. That's what's going on today.

Nancy: Another related idea is using Norway's hydropower system as a kind of a giant battery. Many of Norway's hydropower plants have an upper reservoir and and lower reservoir — with a combined water storage capacity equal to roughly 60 percent of all the water that flows into these reservoirs. There's a historical reason for this: much of Norway's precipitation comes in the form of snow, so the Norwegian government made sure that there would be enough reservoir capacity to generate electricity in the winter, when the demand is the highest.

Ole Gunnar: 118(14:16) So this is this is a neat thing with the Norwegian system is that we have a lot of dams, we have more than 1000 dams. And in that dam, we have a lot of water. And that water when it is in the dam, it's it's a battery. And that battery is 87 terawatt hours. That is approximately I would say 60 to 70% of the Norwegian annual utilisation of energy. So that's quite a big battery. Let's say we utilise that battery different. So when the wind stops to blow or the storm is coming, we could utilise that water in a shorter time when we need it. And then we stop the hydropower plants when we have enough wind.

Nancy: In days when there is more renewable energy being produced than can be consumed, that energy can be “stored” by using it to pump water from a lower reservoir to the upper reservoir. Then when you need that electricity back, you just run the water that you stored in the upper reservoir through the hydropower plant and generate electricity with it.

But as Ole Gunnar said, the turbines aren't designed for this kind of off again, on again stress. Enter

Johannes: 136(1:15) Johannes Kverno. I'm a PhD candidate here at the Water Power laboratory, roughly in the middle of my project. And my work is on flexible operation and design of Francis turbines.

Nancy: Francis turbines are a kind of turbine specifically designed to handle water flows with lots of energy and pressure — which are exactly the kinds of conditions that Norwegian hydroelectric plants operate with

Johannes 136 (3:19) With more energy sources like solar and wind, it will require the rest of the energy producing system to increase their flexible operation scheme to compensate for cloudy days or more wind.

And since hydropower is a really fast acting type of power source, it's very useful and usable to quickly adjust according to the both the demand and the supply. But of course, most of the turbines in Norway at least were designed for more stable operation at close to their design points. So with more flexible operation, there will be more fatigue, which will reduce the lifetime of the runners and increase the cost of operating the plants basically.

Nancy: Here's where being to conduct experiments at scale in the Water Power Lab really helps. By studying how turbines can be designed to handle these new conditions they can make the system that much more efficient.

Johannes: And the hope is that we can use this data to when we're running this in the rig actually say something about what the strain is in the blade and how the design operating conditions will affect the lifetime basically, how it will increase the fatigue loading on the blade.

Nancy: So you're a part of the Green Revolution.

Johannes: Yeah, I kind of feel like I am. Hopefully we'll come up with something that's actually going to be useful for society.

Nancy: And what of the saboteurs and their efforts to blow up the heavy water plant? The short answer is that they succeeded — and all of the saboteurs were able to get away safely. Five of them skied more than 300 km east, to the safety of Sweden, while the rest remained to continue their work against the Nazis. The Germans got the heavy water plant up and running again within a matter of months, but Allied bombers destroyed the facility again, and the Germans abandoned the plant in 1944. We know now that the Germans never did produce a bomb — but that was not known at the time.

As for Vemork itself — it's still producing electricity, in a refurbished facility with two highly efficient, 100 MW turbines, built by one of the two original Norwegian companies that helped support the Water Power Lab — Kværner.

Nancy: I'm Nancy Bazilchuk, and you've been listening to 63 degrees North, an original podcast from the Norwegian University of Science and Technology. If you'd like to learn more about the speakers on today's program, or look at some of the academic publications used to write this script, check out our show notes. Sound design, and editorial help from Historiebruket. Thanks for listening.