DRaaS - Project Report

Cryogen dilution refrigerators (DRs) using Helium-3 and Helium-4 isotopes for excessive, continuous cooling needs are rapidly becoming the leading method for achieving millikelvin temperatures. These refrigerators are used to cool vital computer components like computer chips, photonics, spintronics, and other condensed matter. These are especially helpful in fields such as quantum computing and nuclear research, where product cooling is essential. Employment in sectors such as space and innovation, among others, are major growth drivers for the market for cryogen-free dilution refrigerators. The constant need for a substance, commodity, or invention to supplement the cooling of objects at a specific desired level, the need for an efficient storage facility for liquid nitrogen and liquid helium in interstellar operations, and the failure of cooling powder as a cooling agent in advanced operations are the main factors driving the cryogen dilution refrigerator market and stroking it with abundant demand.

Outline

Technical Background Information

Physical background using the example of condensed matter physics and quantum device physics

Nowadays, state-of-the-art research in condensed matter physics is often based on measuring quantum effects. These effects appear for example, when particles are restricted to occupying states with discrete energy levels. The energy needed for or released during transitions between two levels is quantized. Quantum effects are investigated and used in various areas of condensed matter physics, such as optics, electronics, or scanning probe microscopy. Temperature is related to the energy of particles and the broadening of the energy levels. If the temperature is too high, the energy levels overlap and no discrete states and transitions can be identified anymore, features in the measurements broaden and the measurements can be noisy. As an example, room temperature corresponds to an energy of about 25 meV, a temperature of 4 K (temperature of liquid helium) to an energy of about 0.34 meV, which is still too much to observe a lot of quantum effects. Moreover, the reliable operation of devices based on such effects, including quantum information technology devices like superconducting qubits, is not possible. Therefore, intensive cooling of the samples to low temperatures down to the mK regime is required.

While older cryostats are based on a “wet” technology that requires regular refilling with liquid nitrogen and/or helium, modern “dry” DRs do not require external supply of cryogenic liquids. The advantages of the latter are therefore improved temperature stability as well as highly automated operation, which are both beneficial to run long experiments, e.g., measuring several days or weeks on a single device, as even a slight increase of the temperature to several K can disturb a quantum device and change its properties.

Measurement equipment requirements

Depending on the kind of research experiment, there are different demands on the measurement equipment installed inside as well as outside of the DR. This can include the need for optical components like lenses, magnets which can generate magnetic field of several tesla, or shielding from vibrations or external magnetic fields. To conduct electrical measurements, as they are for example needed for superconducting qubits, spin qubits, or electrical measurements of topological insulators, various electrical components such as appropriate DC or radio frequency (RF) cabling, measurement instruments and power supplies (e.g. lock-in amplifiers, arbitrary waveform generators), as well as other components like bandpass filters can be required.

Steps that need to be performed to conduct measurements in a DR

Starting point: fully fabricated chip, usually having one or several device structures which are to be measured.

1. Mounting the chip on a chip carrier
2. Loading it into the DR
3. Performing the cabling required for the specific measurements
4. Cooling down the DR
5. Conducting the measurements
6. Heating up the DR
7. Unload the chip carrier with the chip from the DR
8. Demount the chip from the chip carrier (optionally)

Time requirement for the different steps

- Steps 1-3: ~ 1 day
- Step 4: 1-2 days
- Step 5: 1 day to 1 month (even longer if the devices are promising and a lot of different and high-resolution measurements can be conducted)
- Step 6: 1-2 days
- Step 7-8: several hours

Further details on steps 1 and 2

The sample to be measured is usually a chip, e.g., a Si chip, on which material has been deposited and micro-/nanostructure devices have been fabricated, most commonly in a cleanroom environment. For measurements in a cryostat, chip sizes usually range from several mm to 1-2 cm.
To mount a chip into the DR, a chip carrier/sample holder is needed which fits into the special DRs. Depending on the demands of the research experiments, these chip carriers can be commercially bought or self-designed.
To conduct electrical measurements, the device structures on the chip have to be connected to the DR cabling via the chip carrier. The chip carriers are designed to provide the required contacts. The most common way to electrically connect the device structures to the chip carrier contacts is by wire bonding.

Further details on step 5

Usually in research experiments, the specific measurements which are conducted in the DR highly depend on the device/sample and experiment details and the device quality. Sometimes basic measurements taking a few hours or days are enough to evaluate if, for example, the device structure has to be improved or if the device is broken (nanostructures are quite sensitive and can easily be destroyed by scratches, electrostatic charges, etc.).

Basic calibrations, for example, finding the resolution frequency of superconducting qubits can take days to weeks.

If a device is promising and a lot of different experiments can be conducted, measurements can take up to several weeks or months. In general, measurements which require sweeping several parameters successively (e.g., different applied voltages or currents) and high-resolution measurements (e.g., with a small stepping between applied voltage values) take longer time, e.g., up to several days for one single measurement after it has been started.

DR examples from other research groups:

1) The data below corresponds to the dry DR at Sabanci University. The size of the system is not small.
   Preparation (including vacuum, cooling, etc.): dry in 3-4 days, wet in half a day to 1 day.
   Measurement: depending on the sweeping magnetic field, temperature and gate vary between 1 day to 1 month depending on range and sweep rate
   This case can afford 70-100 customers in a year, assuming 15 days for each experiment on average.

2) Information from a group at RWTH Aachen University/FZ Jülich (this is a comparably new group, but it has an exceptional amount of money and will probably become one of the biggest research groups on (superconducting) qubits in Europe):
   They own two dry DRs from Bluefors with base T = 10 mK at the moment. One has been working non-stop for 1-2 years now. The other has down times of about 50%, e.g., due to leakage problems. Troubleshooting (by Postdocs or Ph.D. students) takes one to several days. If there is leakage, the company has to exchange that whole part of the DR, which takes much more time (shipping, etc.). The group aims to have 10 DRs next year, to ensure that at least 6-7 will

always be working. The DRs are already ordered, but delivery times are long (usually several months at least).

The time to exchange a sample is about a week: Around two days for heating up, one day for unloading and loading the samples (all shields have to be dismounted to reach the inner part of the DR, cables have to be de-/attached,... There are other DRs, e.g., “Triton” from Oxford, which work as bottom loaders and enable faster exchange, but they have other drawbacks, e.g., stronger limitations in sample size and the number of cables) and around two days for cooling down. Time can be used more efficiently by starting the heating or cooling process on a Friday and letting it run over the weekend.

Measurement: Calibration of the qubits can take a day to several weeks. More measurements and higher resolution measurements generally require more time. The group uses control software and measurement programs based on QISKIT to do remote experiments, e.g., conducting measurements while traveling by train is possible. For this, they chose measurement instruments where they do not need to replug cables on site. They have cooperation with Zurich instruments to optimize the measurement instruments and software according to their needs. These optimized instruments are usually also sold regularly to other customers. The research group also developed part of the software (especially the feature of working remotely) themselves. It is not openly available because of the amount of work required to do proper administration.

Examples of downtime of DRs

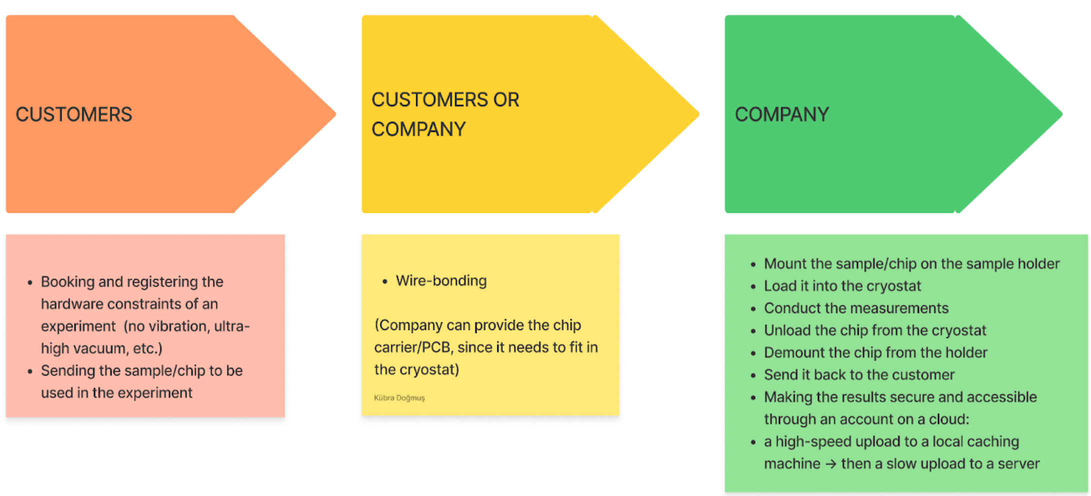
- There are several months (sometimes up to a year) where the DR is not being used in the Sabanci University, Qtnel group since there is just one group that uses DR. About four months in a year (including summer and Christmas holidays) in PSI (Paul Scherrer Institute), Neutron and muon group, in Switzerland and also in IFW Dresden
- On the other hand, there are research groups that own several DRs, and there is almost no downtime in the sense of “DR is working, but nobody is measuring” because there is a queue of researchers who want to use the DR (Information from five groups at RWTH Aachen University/FZ Jülich and RIKEN CEMS). However, there can be up to a few weeks or even months of downtime for a DR when it breaks. This downtime is composed of troubleshooting by researchers on-site and, if necessary, waiting for a replacement part to be sent.

Problem

Many laboratories and startups cannot afford the expenses, space, and time to purchase and build their own dilution refrigerators (DRs) because of not having enough budgets or enough time to train people, etc., despite the growing need for ultra-low temperature facilities. On the other hand, there are some labs and companies that do not use the full capacity of their DRs. Note that there are some labs, but they also need to spend several months, in addition to corresponding costs for training people to be able to work with DRs. Moreover, DRs need to be fixed due to different problems that may occur, such as leakage or other maintenance, so DR users need to wait for a technician for several weeks to resolve the issue (downtime).

Solution

DRaaS (Dilution Refrigerator as a Service):
In our business model, anybody in need of a DR may get one as a service without having to buy any equipment upfront. In our model, we introduce a platform like AWS that users can easily connect to labs and companies that are able to perform customers' experiments needed DRs. We present two approaches in our business model: 1) introducing a platform to connect customers and owners of DRs, like Airbnb, and 2) having a lab with several DRs to provide service to customers who need DRs, in this approach, we need to attract investors to invest money in setting up our DR lab.

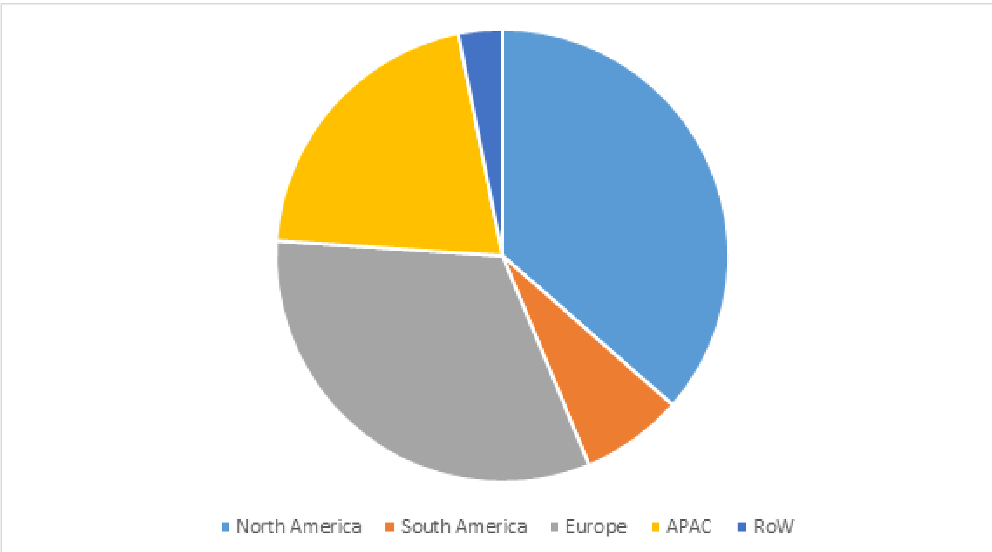


Market Analysis

There are different markets for DRs based on the base temperature. In 2020, a base temperature of less than 10 mK will account for 42 percent of the market. Various temperatures are required for the detection of dark matter, the detection of low-energy neutrons, X-ray astronomy, and spectroscopy. For millikelvin-temperature cooling, bolometric astroparticle detectors use dilution refrigerators. In October 2020, Oxford Instruments released the world's coldest dilution refrigerator. The Proteox5mK combines the most powerful dilution unit from Oxford Instruments and active gas gap heat switches to achieve base temperatures of less than 5 mK. At high temperatures, quantum events are obscured by thermal noise. The lower the temperature of a substance, the more they can learn about its quantum qualities. Researchers may describe quantum states such as Majorana Fermions and Fibonacci Particles by using the Fractional Quantum Hall Effect. These factors promote market expansion.

The DRs are applied in different market sectors. The nano research sector had the largest market share in 2020, with a compound annual growth rate (CAGR) of 24% between 2021 and 2026. Nano research is a branch of science that contributes to the revolutionization and enhancement of several industries and technical fields, such as environmental science, food safety, transportation, medicine, homeland security, and information technology. It is one of the most rapidly emerging scientific fields, having the potential to change several industries. In addition, the National Nanotechnology Project (NNI), the U.S. government's R&D initiative, got more funding than sought in 2017 and 2018, receiving $1.4 billion in 2018 and $1.2 billion in 2017, respectively. The Department of Health and Human Sciences (HHS), the National Science Foundation (NSF), the Department of Energy (DOE), the Department of Defense (DOD), and the Department of Commerce account for the biggest proportion of government investments (DOC). For 2019, NNI proposed a spending plan that allocated 39% for fundamental research, 28% for the development of applications and devices, and 16% for infrastructure and instrumentation. Such financing and investment in the next few years would stimulate market expansion.

In 2020, North America dominated the market with a 35 percent share. Rigetti UK announced in September 2020 that it would lead a £10 million consortium to expedite the commercialization of quantum computing in the United Kingdom. The three-year effort will construct and run the first quantum computer in the United Kingdom; make it accessible through the cloud to partners and consumers; and explore practical applications in machine learning, materials modeling, and finance. Such expenditures in quantum computing result in an increase in the use of cryogen-free dilution refrigerators, which has a beneficial effect on market growth. Countries such as China, Japan, South Korea, and others are investing in R&D to make new goods at a reduced price rather than importing or purchasing the technology. This is expected to result in a large increase in the APAC market throughout the forecast period. The figure below shows the DRs market share in different regions [1].



Global Cryogen Dilution Refrigerators Market Share, By Region, 2020

Global key players of Dilution Refrigerators: Bluefors Oy, Oxford Instruments NanoScience, Leiden Cryogenics BV, Air Liquide(Cryoconcept), Cryomagnetics, Janis Research Company, NanoMagnetics Instruments, ICE Oxford Ltd., Quantum Design Inc., Leiden Cryogenics, Entropy, LTLab Inc.

- The top three players occupy a share of about 36% of the market.
- Europe is the largest market, with a share of about 42%, followed by North America and Asia-Pacific.
- In terms of products, Base Temperature Below 10 mK is the largest segment, with a share of over 57%.
- In terms of applications, Quantum Computing is the largest market, with a share of over 64%.

The global Dilution Refrigerators market size is estimated to be worth USD **118 million** in **2022** and is forecast to reach a readjusted size of USD **177.1 million** by **2028** with a CAGR (compound annual growth rate) of **7.0%** during the review period [2]. In another survey, we found similar results as follows, the global cryogen dilution refrigerator market was valued at USD **112.1 million** in **2019** and is projected to reach USD **211.4 million** by **2027**, expanding at a CAGR of **9.1%** during the forecast period. In terms of volume, the global cryogen dilution refrigerator market is expected to expand at a CAGR of **8.1%** during the forecasted period [3]. Moreover, another research predicts that the value of the Cryogen Dilution Refrigerators market could be **236 million** USD by **2028**. The CAGR of Cryogen Dilution Refrigerators is **14%** from **2022** to **2028** [4]. Europe was the largest revenue market, with a market share of **47%** in **2017** and **46%** in **2022**. In **2022**, North America's market share was **25%**, ranking second. With the improvement of the economic level, the downstream demand continues to expand, and the technological level of these regions continues to improve, which will further promote market development [4]. Cryogen Dilution Refrigerators companies are mainly from Europe; the industry concentration rate is high. The market share of the top three companies in **2021** was **70%**. The top three companies are Bluefors Oy, Oxford Instruments NanoScience, and JanisULT, with a revenue market share of **39%**, **23%**, and **7%** in **2021**.

Cryogen Dilution Refrigerators Market Drivers

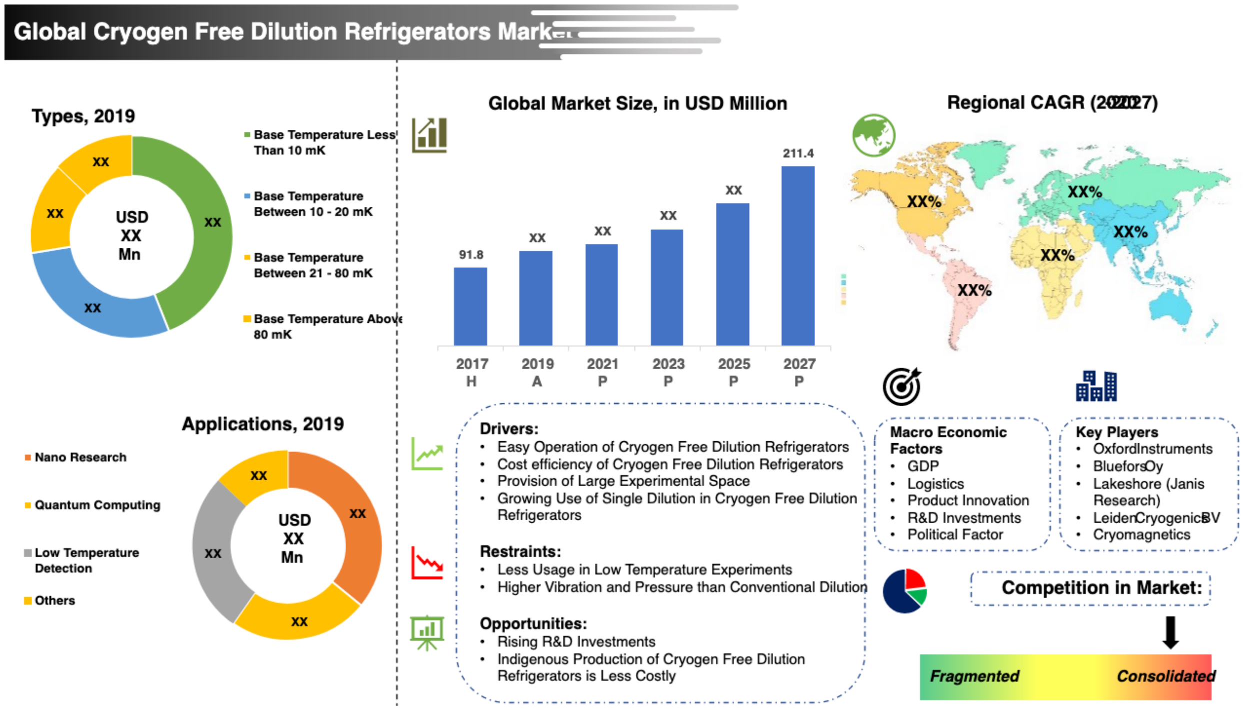
- Rising Applications for Quantum Computing
- High cooling power can be obtained even in a low-temperature region
- Easy Operation of Cryogen Dilution Refrigerators
- Provision of Large Experimental Space

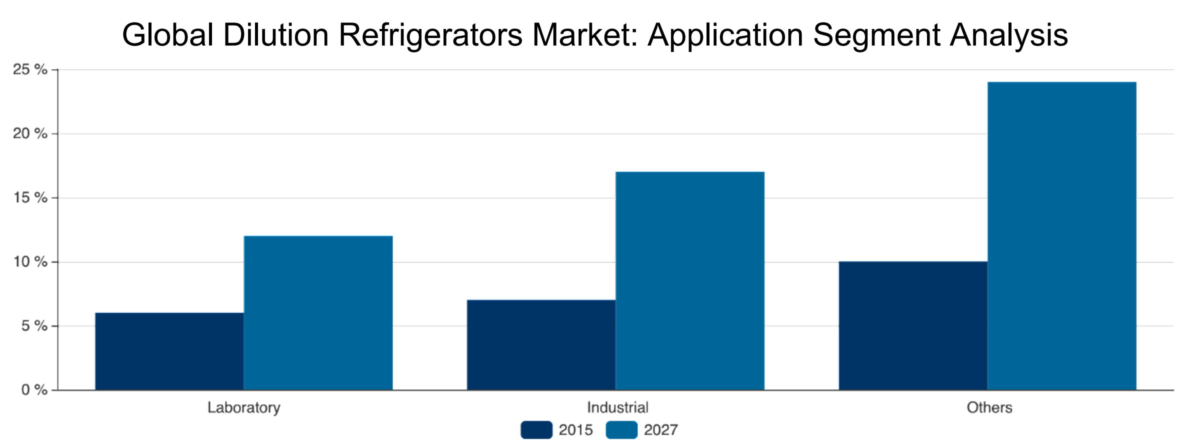
Cryogen Dilution Refrigerators Market Challenges

- Higher vibration and pressure than conventional dilution is expected to hinder the Cryogen Dilution Refrigerators market growth

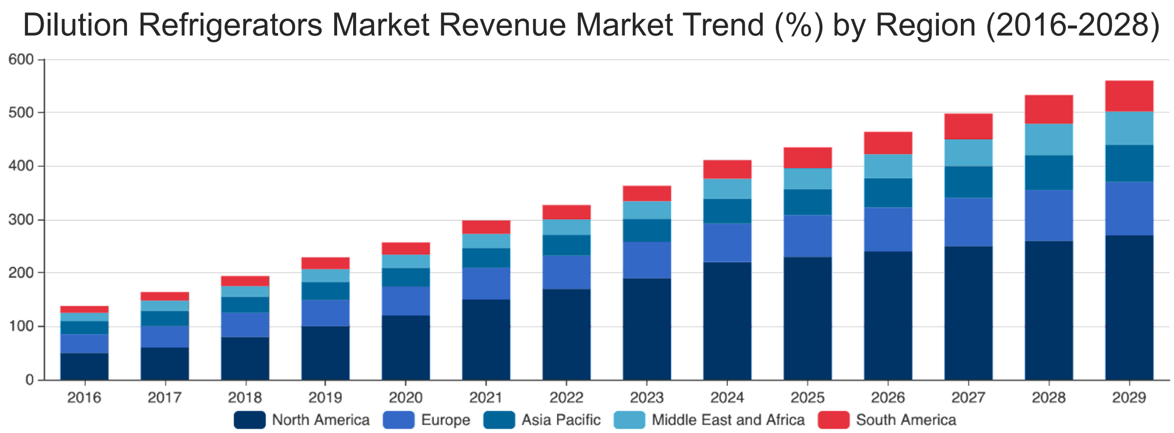
Cryogen Dilution Refrigerators Market Opportunities

- Rising R&D Investments





Figures are for representative purposes only. Market share not depicted as per actual scale. To understand the trends and dominating segments of the Dilution Refrigerator market [5].



The above graph is for illustrative purposes only.

In summary, we mention the important parts of our market research as follow,

- The segment with a base temperature of less than 10 mK is anticipated to account for the majority of the market in 2020 owing to its capacity to rapidly transfer material samples without needing extra days for temperature change.
- As DRs are employed to cool quantum computing processors, and in quantum-optical research for the investigation of luminescence centers in silicon, the market for quantum computing is anticipated to expand at a quick pace throughout the forecast period.
- APAC is predicted to contribute more to the worldwide cryogen dilution refrigerator market from 2020 to 2025, on account of factors such as growing industrialization and economic growth. The firms in this area are increasing their research and development efforts to enhance technology.

Cost Estimations

<u>Running costs:</u>

- Rooms: labs, offices
- Power consumption of a DR (energy price 0.35 € per kWh on average in Europe and power consumption estimation of a DR 52 Mwh per year)
- Technical staff for maintenance and measurements ~ *500 k€ per year*
- Data storage: security and maintenance of servers

One-time costs:

- DR cost: 0.3 - 0.75 *k€* depending on the size of the DR
- electronics + servers: *~1 M€ electronics*, depending on the quality of electronics [*Source:* several research groups at RWTH Aachen University/FZ Jülich, using e.g. Bluefors dry DRs with base temperatures of 10 mK and equipment to measure superconducting qubits]

Occasional costs:

- Shipping of samples back to the customers: *negligible*

Business Model of Platform

We want to connect existing labs, including DRs to customers who need this fridge as a service.

Servers and equipment costs: 0.5 M€
Staff cost: 0.2 M€ annually
Assuming the lifetime of servers are ~10 years
Total cost: 0.25 M€ annually (monthly 21 k€)

We can provide a platform and take 20% of the total benefit as a connector. Cost for providers (Energy, technician): ~0.2 k€ per day and DR. Daily rental service can be considered at 1 k€ per service, so the daily benefit is around 0.8 k€ per service (0.64 k€ for the provider and 0.16 k€ for our platform).

Therefore, if we connect five monthly services, we can cover the cost of our platform, and the more connections we make between providers and customers, the more revenue.

Business Model of Having a Lab

We want to have a lab with **3 different DRs** cost: ~1.2 M€ + and electronics and servers ~3 M€ + staff cost of 1 M€. Therefore, the total cost for our proposed lab is about 5.2 M€.

Assuming the lifetime of a DR is ~10 years:
0.4 M€ annually (for DRs and electronics and servers) + 1 M€ (for staff); hence, the total cost for our lab is 1.4 M€ annually.

Daily cost is ~1.3 k€ per DR

We can provide only daily rental service at 3 k€ so the profit is around 1.7 k€ per DR, therefore we have a profit of around **1.8 M€** annually from our lab (excluding the cost of a place for labs and staffs' offices and electricity power bill).

Pricing Model for Having a Lab

Similar to AWS's *pay-as-you-go* pricing model:

- Daily, weekly, monthly subscription options: 3 k€, 18 k€, 70 k€
(profit estimation on daily, weekly, monthly renting: 1.8 M€*, 1.4* M€*, 0.75* M€*)*
- Optional: Pay less by using more: 2 k€ per day for over six months of usage

Optional Wire-bonding Service

Since the wire-bonding process is one of the crucial steps in performing experiments that need DRs, we can also provide additional wire-bonding services as an option for customers. The cost of having a wire-bonding apparatus in our lab is from 10 k€ to 200 k€; hence, customers need to pay more to use this optional service.

Customers (Opportunity)

Academic users and SMEs (estimated numbers ~5000 and ~70000) [6]

Different sectors are mentioned in our market analysis. As an example, quantum computing could create up to $850bn of value globally over the next 15-30 years. The past two years have seen a big step up in global investment in quantum. In 2021, equity investment in quantum computing startups increased eight times in comparison to 2019.

Customers' Demands

This analysis will be done after acquiring enough potential customers to understand their needs. As a principle, a product is built to cover the needs of 80% of the customers.

The Advantages of Our Models

- No upfront costs
- Time advantage: experiment results in a short time
- Globally accessible: no travel requirement to the service point
- Stable power resources reduce the risk of failure
- No storage/installation/maintenance requirements: not wasting time and money regarding training or employing people
- No downtime: technicians available
- Sustainability
- Universities and companies can earn money by renting their DRs during the downtime period

Requirements of Our Model of Having a Lab

- Stable energy resources
- Highly demanded talent for assembling and maintenance
- Providing modified designs for customer
- Estimating the computing cost per unit work
- Scalability

Competitors

In the platform model, research groups' collaboration can be considered as competitors. In the Lab model, there are no other competitors right now, but we will consider current DR producers as competitors, such as Bluefors Oy, Oxford Instruments NanoScience, Leiden Cryogenics BV, Air Liquide (Cryoconcept), Cryomagnetics, Janis Research Company, NanoMagnetics Instruments, ICE Oxford Ltd., Quantum Design Inc., Leiden Cryogenics, Entropy, LTLab Inc.

Collaborations

A partnership is feasible with AWS or Microsoft (as the Womanium team collaborated before) to develop a cloud platform for our service. We can agree with some providers for a lower price in a long-term business relationship, e.g., NIST provides 20% of the market price of liquid nitrogen/helium for some customers.

Our Target Geography: Europe

- Based on the fact that the European Union has the highest concentration of QT talent [7]
- Also, as mentioned earlier, Europe has the biggest cryogen dilution refrigerator market.

Current Market Size

- **TAM** (Total Available Market): global dilution refrigerator market → **$118 million**
- **SAM** (Service Available Market): target service region is Europe → **$54 million**
- **SOM** (Service Obtainable Market): SMEs and research teams that can't afford to have a DR constitutes → **$18 million**

Investment Opportunities

★ Hardware startups get the biggest share of funding [7]
★ The highest investment has been done in superconducting qubits that require DRs [7]

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