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An Innovative Heating, Ventilation, Air Conditioning and Refrigeration Circular Economy System for Reducing Carbon Dioxide Emissions in Europe via Extensive Reuse of Existing Fluorinated Gases

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Abstract: Reducing emissions from fluorinated gases (F-gases) is considered one of the key conditions for the European Union (EU) to be able to meet the requirements of the European Green Deal, primary objectives of which are the reduction in greenhouse gas emissions by at least 55% by 2030 compared to 1990 and the gradual transition to net climate neutrality by 2050. To this end, a quota system for hydrofluorocarbons (HFCs) is already in place, introduced through the updated F-Gas Regulation (517/2014). The aim of this paper is to review an innovative scheme currently under development that strongly promotes the Recovery, Recycling and Reuse (3R) of F-gases extracted from the heating, ventilation, air conditioning and refrigeration (HVAC-R) equipment of the building sector, thus offering a sustainable alternative source for refrigerant supplies. Therefore, the basic operating principles of the so-called "3R ECOSYSTEM" are outlined and especially its three main components, which are: the self-certification/self-declaration platform, the F-gas identification and recycling units (prototypes) and the Retradeables marketplace. In addition, an overview of both the demonstration phase and the scheduled replication phase of the 3R ECOSYSTEM is provided, including the estimated impact on carbon dioxide (CO_2) savings due to the progressive uptake of the circular use of existing F-gases across Europe.

Keywords: Retradeables project; 3R ECOSYSTEM; circular economy; used F-gases; recovery; recycling; reclamation; HVAC-R systems; reduction in CO_2 emissions; Europe's decarbonisation

Citation: Barmparitsas, N.; Karellas, S.; Pallis, P.; Thanopoulos, S.; Kobelt, D. An Innovative Heating, Ventilation, Air Conditioning and Refrigeration Circular Economy System for Reducing Carbon Dioxide Emissions in Europe via Extensive Reuse of Existing Fluorinated Gases. *Energies* **2023**, *16*, 7705. https://doi.org/10.3390/en16237705

Academic Editor: Antonio Zuorro

Received: 29 September 2023
Revised: 13 November 2023
Accepted: 16 November 2023
Published: 22 November 2023

1. Introduction

1.1. HFC Phase-Down

Between 1990 and 2014, EU F-gas emissions increased by around 70%, representing almost 3% of all greenhouse gas (GHG) emissions. This increase was mainly due to the replacement of ozone-depleting hydrochlorofluorocarbons (HCFCs) with HFCs in the HVAC-R sector combined with the growth of this specific sector as a whole [1]. Under such exceptional circumstances, the EU took regulatory action by publishing a new F-Gas Regulation (EU No 517/2014), which replaced the original F-Gas Regulation (EU No 842/2006), reinforcing previous measures and introducing additional requirements to achieve the progressive reduction in HFC consumption as well as the transition to refrigerants with a lower global warming potential (GWP) [2,3].

Basically, the most significant new requirement introduced by the 2014 EU F-Gas Regulation was the phase-down of HFCs, aiming to drastically change the way the HVAC-R industry deals with F-gases. For this purpose, an economy-wide mechanism has been in place across the EU since 2015, whereby producers and importers are allocated annual quotas of HFCs, expressed in CO_2 equivalent (CO_2e). Based on the existing schedule, a

79% reduction in HFC consumption has to be gradually achieved by 2030, compared to "baseline" levels, which are officially identified as the maximum amount of HFC quotas available in 2015 and corresponding to 100% of the annual average demand over the period 2009–2012, approximately 182.5 million tonnes (Mt) of CO_2e. Moreover, the expected reduction in the use of HFCs in the HVAC-R sector will enable EU F-gas emissions to be cut by two-thirds by 2030 [4–6]. In total, the HFC phase-down will reduce cumulative HFC emissions by 1.5 Gigatonnes (Gt) CO_2e by 2030 and 5 Gt CO_2e by 2050 [2,5].

Under the HFC phase-down enforced by the 2014 EU F-Gas Regulation, all stationary and mobile sectors in each EU member state compete for the same pool of HFC quotas, unless exempted. In addition, the HFC phase-down applies to bulk quantities of virgin HFCs, regardless of whether they are produced inside or outside the EU. After that, all refrigeration, air conditioning and heat pump equipment that is pre-charged with HFCs is, from 2017 onwards, covered by legally binding HFC phase-down quotas [3–5].

Furthermore, there are two key assumptions under the 2014 EU F-Gas Regulation: the first one is that the HFC phase-down only applies to bulk quantities of virgin HFCs, regardless of whether they are produced within or outside the EU. This implies that recycled and reclaimed HFCs are not considered as "placed on the market" (POM), thus excluding them from all the imposed legal restrictions described above [3–5]. The second assumption is relevant to the full implementation of containment and recovery provisions, indicating that operators and contractors are obliged to take all precautionary measures to mitigate leakage from HVAC-R equipment and ensure end-of-life recovery. Therefore, only technicians who have been trained and certified by competent national bodies are authorised to carry out installation, maintenance, decommissioning, leakage checking and recovery services for equipment containing F-gases [3,7].

Recently, the European Parliament and the Council reached a provisional agreement on strengthened existing rules to further reduce GHG emissions from F-gases and ozone-depleting substances (ODS) by 500 Mt CO_2e by 2050. Regarding F-gas emissions, the agreed package of measures is considered to prevent 40 Mt CO_2e by 2030 and 300 Mt CO_2e by 2050, on top of the amount that could be achieved under the 2014 EU F-Gas Regulation. The upcoming reinforcement of the current F-gas legislation is intended to facilitate the achievement of the EU's climate targets of at least 55% emission reductions by 2030 and climate neutrality by 2050. At the same time, it will also ensure the EU's over-compliance with all the rules of the Kigali amendment to the Montreal Protocol [8–10].

Under the 2016 amendment, which came into force in 2019, HFC consumption levels for the EU and other developed and developing countries worldwide should be 15% of 2019 levels by 2036 [11,12]. Global implementation of the Kigali Amendment would prevent up to 80 Gt CO_2e emissions by 2050 [1,12]. This would also make a significant contribution to the Paris Agreement's objective of limiting global temperature increase to well below 2 °C [6,12]. Overall, the EU has been on track to comply with its obligations under the Montreal Protocol: in 2022, EU-27 HFC consumption was 55% below the Montreal Protocol target, recalculated to the EU-27 geographical scope [1].

1.2. Background and Scope of the Study

Daikin Europe N.V. (DENV), Daikin Central Europe (DACE), the National Technical University of Athens (NTUA) and the Society for Materials and Energy Applications (MAT4NRG GmbH) are the four partners of the consortium behind the Retradeables project that receives EU funding. The key objective of the ongoing project is to realise the first circular economy ecosystem to strongly promote the efficient management of used gases, offering sustainability and accountability to the HVAC-R industry and reducing environmental pollution stemming from F-gas emissions. This is exactly the mission of the so-called "3R ECOSYSTEM" that is currently under development to bring total innovation to the HVAC-R industry, adding value to used refrigerants that will be treated as an asset instead of a waste to be destroyed.

Therefore, an online platform has already been realised as a key work product of the Retradeables project to demonstrate the circular economy of used refrigerants driven by a market mechanism. Indeed, this is the first European trading platform to offer a user-friendly solution for existing refrigerants by creating a simple, viable online marketplace that strongly supports the selling and buying of used F-gases [13]. In practice, the marketplace platform will enable the HVAC-R industry's gas stock to be boosted with used HFCs reclaimed according to their original industrial standard, thereby compensating for the limited supply of virgin gases due to the HFC phase-down. Furthermore, a significant prevention of CO_2e emissions will also be achieved as a direct result of increasing the levels of recovery, recycling and reclamation of used F-gases, thus contributing to the fulfilment of the ambitious targets set under EU and international climate and environmental policies.

Secondarily, the project falls under the "Removal of barriers posed by standards" work area, as it has also focused on the development of a self-certification/self-declaration scheme to validate the high quality of the recycled/reclaimed F-gases traded on the marketplace platform. In particular, the Retradeables project proposes a new approach that will unify criteria towards a unique certification system for the recovery and proper treatment of F-gases across the EU. To this end, a coherent and robust methodology for (field) installers has already been designed to provide them with all the necessary knowledge and practical skills required to sample, analyse and characterise recovered refrigerants in real time and on site. In addition, a centralised database storing all key transaction data will guarantee regulation compliance and full transparency in the individual steps of F-gas recovery, F-gas composition analysis as well as F-gas classification in terms of quality and quantity, respectively. Current barriers have been mapped and specific replication and transfer measures have been defined to be implemented to ensure the feasibility of the 3R ECOSYSTEM at an EU-wide level. In addition, a thorough Dissemination and Communication Plan, including training activities dedicated to qualified users will help engaging relevant stakeholders to foster the deployment of the 3R ECOSYSTEM.

Against the above background, this paper aims to adequately describe all the key innovation elements of the 3R ECOSYSTEM and illustrate its potential contribution to the EU's decarbonisation efforts. Hence, the estimated environmental impact due to the recovery and recycling/reclamation of used F-gases is indicated in terms of CO_2e reduction. The reported key performance indicators (KPIs) refer not only to the demonstration phase but also to the replication phase that will start immediately after the end of the project. Finally, a comprehensive overview of both the progress status of the Retradeables project and the proposed roll-out schedule is provided.

2. Outlining the 3R ECOSYSTEM

2.1. Innovative Aspects

The final version of the 3R ECOSYSTEM will consist of three main components: (i) a self-certification/self-declaration platform, (ii) the F-gas identification and recycling units (prototypes) and (iii) the "Retradeables" marketplace platform (Figure 1). This circular economy scheme is considered to incorporate all the necessary framework and tools to provide a sustainable market-wide solution for:

1. The alternative management of used F-gases at the end-of-life of HVAC-R systems by enabling the recovery of all refrigerants in the installed base. The two possible options are then either reuse through recycling/reclamation or appropriate disposal (if reuse is not possible). For this purpose, three F-gas quality grades have been specified [14]:
    - A-grade refrigerants that can be recycled via a recycling machine and reused.
    - B-grade refrigerants that must be reclaimed in a distillation factory.
    - C-grade refrigerants that are contaminated to such an extent that they require destruction by certified means.
2. The establishment of an online high-end marketplace to connect the relevant parties interested in trading their own recovered F-gases. The transparency and traceability of the transaction (price included) is regarded as an absolutely innovative aspect, as

there is currently no fixed price index for recycled/reclaimed F-gases. Indeed, the Retradeables marketplace is intended to act like the stock market. This means that demand and supply are analysed and average prices for traded F-gases are displayed to all participants.

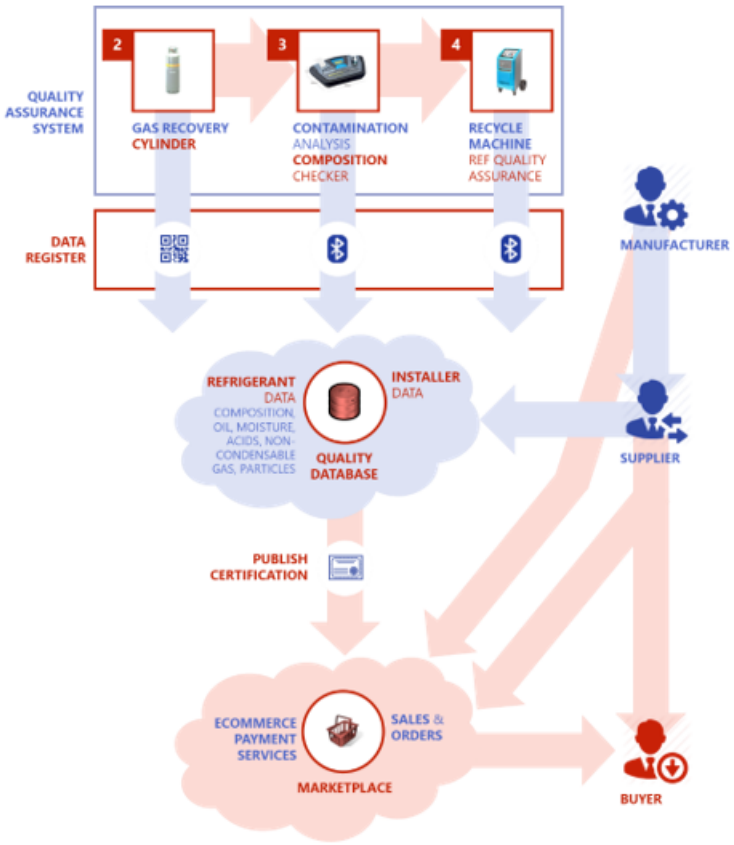

Figure 1. Overview of the "3R ECOSYSTEM" structure after the final implementation.

The very basic operating principles and other critical aspects of each of the three components of the 3R ECOSYSTEM are outlined below.

2.2. Self-Certification/Self-Declaration Platform

The self-certification/self-declaration platform will serve as a powerful tool to redefine the recent classification of existing refrigerants as "hazardous waste" by involving stakeholders (mainly installers) to implement the proposed methodology and input all necessary data on the recovery process in real time and on site. This approach will lead to a smoother transition towards a more easily regulated F-gas market driven by the HFC phase-down and create a value proposition for recovered F-gases. In particular, there are two possible practices for the evaluation of the F-gas quality grade (A/B/C grade):

- Self-assessment: making use of the HVAC-R unit's logbook. This is the current practice applied by F-gas technicians (self-declaration schemes).
- Measurement: making use of the HVAC-R unit's logbook in combination with the initial analysis results of the portable composition analyser. This is the intended practice (self-declaration and self-certification schemes).

Overall, the integrated self-declaration and self-certification schemes are expected to play a critical role in establishing a reliable and efficient HVAC-R circular economy by operating an accurate database and eliminating low-quality recycled refrigerants from the market.

Database Design and Development

Given that easy access to the self-certification/self-declaration platform is a key factor, the definition and categorisation of all individual parameters considered as data entries have already been defined. These are related to the client, the HVAC-R unit, the extraction location and date, as well as the F-gas quantity and quality (A/B/C grade). The structure and architecture of the platform also includes filtering, constraints, mandatory fields and other features to further improve the user experience, as well as facilitate administrator supervision.

The administrator of the database will be a third party. All necessary tables have been provided to ensure the traceability of all F-gas quantities during the recovery, composition analysis, data logging and reuse activities [15]. In addition, a separate index value will be assigned to each registered user. This index value will be regularly updated based on a wide range of quantitative and qualitative criteria, such as accuracy on the F-gas quality statement, uploading (or not) of composition analysis results and on-time delivery.

Finally, field installers (technicians) will be responsible for printing QR codes and placing them on both the installed HVAC-R unit and the recovery bottle(s)/cylinder(s) to be used. This can be justified by the fact that the relevant data will be inserted into the database via scanning the individual QR codes with a smartphone camera. A QR code scanner application has already been developed for this purpose.

2.3. F-Gas Identification and Recycling Units

The F-gas identification and recycling units (prototypes) under development have been designed to serve as a total solution by combining a portable refrigerant composition analyser with a recovery and recycling unit, both applicable in pure HFCs, such as R32 or R134a, and HFC blends, such as R410A, R407C and R404A. Thanks to the prototypes, F-gas stakeholders (mainly installers) will be able to determine the composition of the recovered F-gas, categorise it by quality and also remove oil and moisture from it, all in real time and on site. The two key components of the prototypes are briefly described below:

- Portable refrigerant composition analyser: Devices of this type are currently commercially available from various manufacturers for determining the purity of recovered F-gases in the HVAC-R market. However, laboratory testing is being conducted under the Retradeables project with the ultimate goal of producing a similar product but with more advanced operating characteristics to provide more detailed F-gas composition analysis data, including oil and moisture contamination rates. Consequently, two different approaches will be utilised in combination: one incorporating existing state-of-the-art measurement devices (classic composition analysers) and the other one based on time series analysis of specific thermodynamic parameters (advanced product under development).
- Recovery and recycling unit: Such a unit is now marketable from DENV, one of the key partners involved in the Retradeables project. It is easy to use and can be connected directly or via a recovery pump to the installed HVAC-R equipment. After connecting the cylinder(s), the F-gas recovery and recycling process is automatic. The advantageous feature of this device is the maximisation of the recovered F-gas quality through the three-step recycling mode applied to remove the majority of impurities [16]:
    1. Oil separation and electrostatic filtering.
    2. Filter drier to remove moisture.
    3. Liquid separation via evaporation.

All in all, the use of the prototype in the field is expected to have a very positive impact on installers, as the relevant process flow will be significantly simplified over the current practice, while the corresponding outcomes will also appear much more upgraded and accurate. During the last stage of the development of the prototype unit, the recovery and recycling machine will be coupled with Internet of Things (IoT) equipment as an

extra feature to enable automatic data upload to the operating database [17,18]. Once the prototype is equipped with the detachable IoT device under development, the final implementation will be tested in the lab and in the field to verify proper data flow. The F-gas identification and recycling IoT unit is then supposed to come onto the European HVAC-R market for sale.

Intercomparison Tests, Validity of Measurements and Performance of the Equipment

Balancing accuracy and precision with the main cost factors (e.g., equipment costs, labour costs, equipment/analyst maintenance) is considered of paramount importance to produce reliable and affordable results. Under this assumption, MAT4NRG GmbH is currently conducting a series of intercomparison tests between the selected analyser and the AHRI 700 Standard Reference Method [19] with respect to all target categories of sampled F-gases and each critical measured substance (oil, moisture, solids, etc.). The findings from this task are needed to confirm the validity of the measurements of the proposed portable analyser [20]. The performance of the recovery and recycling unit in removing oil and moisture will also be verified by measuring the oil and moisture content before and after removal. Final testing will take place when the prototypes are ready for use to determine whether their overall performance is satisfactory enough.

2.4. Retradeables Marketplace Platform

The Retradeables platform is actually the first European online marketplace to support the reliable trading of used F-gases between the various HVAC-R stakeholders, powered by well-defined legal frameworks and secure payment methods. The supply side (sellers) is represented by installers/installation companies, service companies and partner networks that have access to refrigerant through small, medium or large installations. Likewise, the demand side (buyers) is represented by gas distributors/distribution companies and gas producers. Therefore, the former parties can benefit from an additional revenue and cost reduction stream, while the latter parties can increase the amount of recovered product they receive from the F-gas market, thus easing the pressure on their quota of virgin refrigerant.

Development of the Platform

The Retradeables marketplace was officially launched in May 2021, even before the start of the three demos (SK, HU, CZ) in July 2021. Moreover, it is now considered to be a fully operational platform where all local stakeholders can register online [13]. Built on state-of-the-art technology to provide best performance and ease of use, the Retradeables marketplace supports seamless process flows, including a number of functionalities as outlined below [21,22]:

1. Registration with legal check (F-gas certificate).
2. F-gas recovery data input (at the location of the customer).
3. F-gas quality documentation before and after recycling/reclamation (at the location of the customer).
4. F-gas stock management.
5. Supply and demand management, including aggregation of average prices on the market.
6. Selling of used F-gas (supply side).
7. Buying of used F-gas (demand side).
8. Transactions between installers/installation companies and distributor/distribution companies, including price offers and secure payment methods.
9. Data processing and information generation that are currently not accessible, as there is no mechanism/platform to support the collection and configuration of data directly at the time of input.

From the general setup and architecture to the final solution, the Retradeables marketplace is based on the "Plan Do Check Act" cycle which is an iterative four-step management method used in business for the control and continuous improvement of processes and products. This indicates that the platform will be monitored on a regular basis throughout the demos in order to be appropriately customised and enriched with new features according to additional requirements arising from different users.

3. Impact on Europe's Decarbonisation

The Retradeables project via the 3R ECOSYSTEM fosters a completely innovative concept to be implemented to achieve the reduction in GHG emissions stemming from F-gases (CO_2e), according to the EU climate imperatives. Particular emphasis is placed not only on the efficient F-gas recovery itself but also on proper leakage control, installation, maintenance and service of HVAC-R systems, focusing mainly on small residential units, light commercial units, big commercial units, small heat pumps, industrial units and commercial refrigeration units (e.g., supermarkets). This strategy is quite reasonable as buildings account for 40% of energy consumption and 36% of CO_2 emissions in the EU [23]. In particular, the 3R ECOSYSTEM is expected to allow the replacement of existing HVAC-R equipment installed mainly in the building sector with new equipment of higher energy performance and at the same time with significantly lower life-cycle CO_2 emissions due to the reuse of the refrigerant. Furthermore, it will enable the proper maintenance of the later equipment by ensuring the availability of refrigerant. In addition, the development of a well-established F-gas circular economy ecosystem will assist in a new sustainable business model for the European HVAC-R industry, both facilitating HFC phase-down and creating synergies with several European directives and policies, including the Energy Performance of Buildings Directive (EPBD) [24]. It should be noted that the EC proposed a new revision of the EPBD in December 2021. The Commission's new proposal aims to contribute to reaching the target of at least 60% emission reductions by 2030 in the building sector in comparison to 2015 and achieve climate neutrality by 2050 [23].

3.1. General Assumptions

First of all, the different HVAC-R applications were classified as shown in Table 1. Four high-level types of installed units are considered: residential, commercial, industrial and commercial refrigeration.

Table 1. Standard and high-level classification of HVAC-R equipment.

Category	Standard Classification	High-Level Classification
Split Units	Small Residential Unit	Residential
Semi-Centralised Direct Expansion Systems	Commercial Light Unit	Commercial
Variable Refrigerant Flow Systems	Big Commercial Unit	Commercial
Packaged Units	Commercial Light Unit	Commercial
Mini Chillers	Commercial Light Unit	Commercial
Small Chillers	Commercial Light Unit	Commercial
Medium Chillers	Big Commercial Unit	Industrial
Large Chillers	Big Commercial Unit	Industrial
Centrifugal Chillers	Big Commercial Unit	Industrial
Air Handling Units	NA	NA
REFR-Stationary Light Commercial	Commercial Light Unit	Commercial Refrigeration
REFR-Stationary Big Commercial	Big Commercial Unit	Commercial Refrigeration
REFR-Stationary Big Commercial	Big Commercial Unit	Commercial Refrigeration
H H/P	Small Heat Pumps	Residential
H Boiler	NA	NA

The basic information for each standard unit category (charge, average lifetime of equipment and renovation rate) is summarised in Table 2.

Table 2. Basic information for each unit category.

Type of Unit	Charge (kg/Unit)	Average Lifetime of Equipment (Years)	Renovation Rate (%)
Small Residential Units	1.5	10	10
Commercial Light Units	2.9	10	15
Big Commercial Units	18.8	15	20
Small Heat Pumps	4.0	10	10
Industrial Units	300.0	10	25

Finally, all calculations for the expected quantities of recovered F-gases and CO_2e emission savings are based on the following key assumptions:

1. Split units are considered with R410A.
2. Semi-centralised direct expansion systems are considered with R410A and also with 0.5 kg of extra charge.
3. Variable refrigerant flow systems are considered as a 10HP unit with an additional charge of half the pre-charge.
4. Industrial and small heat pumps are a rough estimation of the market.
5. F-gases GWP is considered to be equal to this of R410A: 1 metric ton of F-gas = 2087.5 metric tons of CO_2e.
6. 1 metric ton = 1000 kg.

3.2. Demonstration Phase

From July 2021 to June 2024, the 3R ECOSYSTEM is being demonstrated in three EU countries, representing about 6% of the population of the EU-27 countries: (i) Slovakia (SK) with 5.46 million inhabitants, (ii) Czech Republic (CZ) with 10.49 million inhabitants and (iii) Hungary (HU) with 9.73 million inhabitants (2021 estimate) [25]. In addition, it has been assumed that the three demos will involve a total of 221,640 HVAC-R applications, including residential, commercial, industrial and commercial refrigeration units. The volume above accounts for approximately 0.2% of the global HVAC-R demand, given that it stood at 110.97 million units in 2018 according to the Japan Refrigeration and Air Conditioning Industry Association (JRAIA) [26]. Exactly because of their representativeness in the F-gas sector, as well as their structure and the large number of partners and HVAC-R units, these three countries (SK, HU, CZ) were selected to act as project demos. Another critical aspect was their high demand for old types of refrigerants. Overall, an annual capacity of 807,655 kg of F-gas is estimated. Considering the average lifetime of each type of equipment, an installed base of 7640 tonnes of F-gas was also calculated for the three demo countries, corresponding to 16 Mt CO_2e. Detailed figures are presented in Table 3.

3.2.1. Estimated Impact

Based on the assumed renovation rate for each type of HVAC-R unit (see Table 2), it is estimated that approximately 1490 metric tons of F-gas will be recovered during the 3R ECOSYSTEM demonstration, leading to a reduction in GHG emissions of 3.1 Mt CO_2e. Both the breakdown per demo and the final results in terms of F-gas recovery and CO_2 emission savings are presented in Table 4.

Table 3. Estimation of installed base for both F-gases and CO_2e emissions.

Country	Type of Unit	Units (Pieces/Year)	Total F-Gas * (kg/Year)	Estimation of Installed Base ** (Metric Tons Refrigerant)	Estimation of Installed Base (10^6 Metric Tons CO_2e)
Slovakia (SK)	Small Residential Units	27,630	41,445	414	0.87
	Commercial Light Units	2500	7250	73	0.15
	Big Commercial Units	700	13,160	197	0.41
	Small Heat Pumps	2085	8340	83	0.17
	Industrial Units	45	13,500	135	0.28
	Commercial Refrigeration Units		27,600	138	0.29
	Total	*30,830*	*111,295*	*1040*	*2.17*
Czech Republic (CZ)	Small Residential Units	27,000	40,500	405	0.85
	Commercial Light Units	7529	21,834	218	0.46
	Big Commercial Units	2524	47,451	710	1.48
	Small Heat Pumps	2325	9300	93	0.19
	Industrial Units	200	60,000	600	1.25
	Commercial Refrigeration Units		69,000	345	0.72
	Total	*37,053*	*248,085*	*2371*	*4.95*
Hungary (HU)	Small Residential Units	144,194	216,291	2163	4.52
	Commercial Light Units	4430	12,847	128	0.27
	Big Commercial Units	2203	41,416	620	1.29
	Small Heat Pumps	2680	10,720	107	0.22
	Industrial Units	250	75,000	750	1.57
	Commercial Refrigeration Units		92,000	460	0.96
	Total	*153,757*	*448,274*	*4228*	*8.83*
Total in Trial Countries		221,640	807,655	7639	15.95

* Total F-gas = (Units) × (Charge); ** Estimation of installed base (metric tons refrigerant) = (Total F-gas) × (Average of life).

Table 4. Breakdown per demo and totals of recovered F-gases and CO_2e emission savings.

Type of Unit	SK: F-Gas Recovered via 3R		CZ: F-Gas Recovered via 3R		HU: F-Gas Recovered via 3R		Final Results	
	Tonnes * F-gas	Tonnes CO_2e	Tonnes F-gas	Tonnes CO_2e	Tonnes F-gas	Tonnes CO_2e	Tonnes F-gas	Tonnes CO_2e
Small Residential Units	41.4	86,516	40.5	84,544	216.3	451,507	298.2	622,568
Commercial Light Units	10.9	22,702	32.8	68,368	19.3	40,227	62.9	131,297
Big Commercial Units	39.4	82,195	142.0	296,373	123.9	258,680	305.3	637,249
Small Heat Pumps	8.3	17,410	9.3	19,414	10.7	22,378	28.4	59,202
Industrial Units	33.8	70,453	150.0	313,125	187.5	391,406	371.3	774,984
Commercial Refrigeration Units	62.1	29,634	155.3	324,084	207.0	432,113	424.4	885,831
Total	195.9	408,910	529.8	1,105,908	764.7	1,596,312	1490.4	3,111,129

* tonnes = metric tons.

3.2.2. Results and Discussion

The Retradeables project is clearly dedicated to the circular use of HFCs recovered from end-of-life HVAC-R systems. This alternative approach is fully aligned with the 2014 EU F-Gas Regulation, whereby only virgin refrigerants (not reclaimed) placed on the market are included in the annual quotas allocated by the European Commission (EC). Therefore, the utilisation of used HFCs recycled or reclaimed according to industry standards is considered a valuable solution to ease pressure on the virgin HFC supply chain, reduce the industry's dependence on costly high GWP refrigerants and achieve HFC phase-down targets both at EU and global level. At the same time, HFCs are the most commonly used F-gases in the EU territory, accounting for around 90% of F-gas emissions [1,8]. This

implies that the reuse of existing HFC stocks will also contribute to the reduction in GHG emissions, expressed in CO_2e, thus satisfying the carbon neutrality obligations arising from both European and international legislation (see Section 1.1). It should be underlined that the contribution of the 3R ECOSYSTEM towards Europe's decarbonisation will not be limited to the 3.1 Mt CO_2e that are to be prevented until the end of the project. Instead, the observed environmental impact will become more and more positive as the number of European countries adopting the 3R ECOSYSTEM will increase according to the existing replication plan.

Nevertheless, the pace of progress of the project has not been as expected until recently. This is mainly due to the fact that the start of the project coincided with the health crisis in Europe caused by COVID-19. As a consequence, the participation of F-gas stakeholders in the marketplace platform was quite low, as the public awareness campaign could not be as intensive as planned due to practical problems related to lockdowns and other similar restrictions for protection against COVID-19. Another critical factor that played a decisive role in the observed lack of interest of stakeholders (mainly distributors) to register in the Retradeables marketplace was the unexpectedly low price of virgin HFCs, which led to a reduced demand for recycled and reclaimed HFCs. In addition, the global chip shortage, as well as the long delays experienced in the delivery of various other components necessary for the development of the prototypes, reversed the original project planning, according to which both units (for pure HFCs and HFC blends) should be ready for use in mid-2022, also supporting IoT functionalities.

The above problematic situation lasted almost until the end of 2022. Since then, significant progress has been made in various key areas of the project, with the consistently low price of virgin F-gases remaining the only constraint. In particular, the prototypes are almost finalised, and the dissemination and communication activities are fully underway, encouraging more and more local F-gas stakeholders to become active users of the Retradeables marketplace. As a result of stakeholder awareness and participation in the marketplace platform, increasing quantities of recovered refrigerants are currently being traded and reused, contributing to the reduction in GHG emissions and most notably to the achievement of the project's respective KPI of 3.1 Mt CO_2e by the end of the demos. Last but not least, the quota system for HFCs (HFC phase-down) will be further tightened based on what has been formally set out in the provisional agreement. The use of HFCs should be reduced by 95% by 2030 compared to 2015, going down to zero by 2050. From 2025, the HFC quota that the Commission allocates every year will also be sold for EUR 3 per tonne of CO_2e. As a consequence of the even more restrictive legislative framework, more and more F-gas distributors will certainly have an incentive to seek alternatives such as the circular economy approach supported by the 3R ECOSYSTEM. In other words, there is a clear momentum for the 3R ECOSYSTEM—especially for the Retradeables marketplace—to act in the near future as an integral part of the business cycle of the HVAC-R industry, as it will gradually expand across Europe.

3.3. Replication Phase

3.3.1. Proposed Roll-Out Schedule

The three ongoing demos are intended to serve as the perfect test cases for scaling up the results of the 3R ECOSYSTEM all over Europe. In this regard, a replication plan has already been set up so that the European uptake of the entire 3R solution can take place immediately after the end of the 2-year demonstration phase. The proposed roll-out schedule is divided into two steps: the first step involves 13 countries where DACE has a strong and mature market (6 EU countries and 7 non-EU countries), while the second step will be gradually deployed involving the majority of the remaining EU countries, as well as the UK (see Table 5).

Table 5. The proposed schedule for the stepwise deployment of the 3R ECOSYSTEM across Europe.

Trial Countries	Slovakia, Hungary, Czech Republic
Step 1	
Immediate expansion *	Austria, Croatia, Slovenia, Poland, Bulgaria, Romania, Albania, Kosovo, North Macedonia, Moldova, Serbia, Bosnia-Herzegovina and Montenegro
Step 2	
2024	Germany, Netherlands, Portugal
2025	Italy, France, United Kingdom (UK)
2026	Spain, Belgium, Greece
2027	Norway, Sweden
Market potential to be assessed	Finland, Ireland

* In the second half of 2024, immediately after the end of the trials in Slovakia, Hungary and Czech Republic.

3.3.2. Estimated Impact

Given the replication strategy described above, impact monitoring will be applied for five additional years after the end of the demos to both feed the cycle of continuous improvement and verify the high performance and feasibility of the 3R ECOSYSTEM in the long term by regularly measuring a dedicated set of KPIs. Indeed, specific environmental quantitative targets have already been identified to be achieved by 2029, including the 3 demonstrations and all 13 replications under DACE territory (i.e., 16 countries in total). Regarding the reuse of F-gases, an annual recovery and recycling/reclamation volume of 400 tonnes per country has been assumed in relation to HVAC-R systems serving the building sector. This full-scale estimate was extrapolated from the European Partnership for Energy and the Environment (EPEE) Gapometer [27] to indicate a potential capacity of 32,000 tonnes of F-gases that can be recovered and recycled/reclaimed cumulatively after 5 years of the demonstration phase. The decarbonisation levels are assumed to reach a total of 65 Mt CO2e, respectively.

4. Conclusions

As the supply of HFCs is phased down and the production capacity of high-efficiency F-gases is also constrained due to the F-Gas Regulation, circular use has a vital role to play in reducing the carbon footprint of the HVAC-R sector across Europe. To this end, the currently developed 3R ECOSYSTEM under the Retradeables project serves as a key driver for the prevention of CO_2e emissions by focusing on the recovery and appropriate treatment of F-gases, in particular pure HFCs and HFC blends. Actually, the proposed 3R solution can be described as the first European circular economy ecosystem to support energy efficiency and the responsible management of used F-gases at the end of the life cycle of HVAC-R equipment. This circular scheme, including three key components (self-certification/self-declaration platform, Retradeables marketplace and prototypes), is expected to deliver a real industry innovation by enabling the economically feasible recovery of used gas stocks that can be redistributed on the market, either as recycled or reclaimed refrigerants matching their original composition.

Furthermore, the reuse of recovered HFCs through the 3R ECOSYSTEM will significantly contribute to the mitigation of F-gas emissions, one of the key policy priorities at European and international level. Based on the established project KPIs, 3R ECOSYSTEM is committed to preventing up to 3.1 Mt CO_2e by 2024 as a direct result of the ongoing EU-level demos (SK, HU, CZ) and up to 65 Mt CO_2e by 2029 (i.e., 5 years after the end of the project) in a total of 16 countries, including the 3 demo countries above and also 13 short-term replications (see Table 5). In addition to the substantial decarbonisation of building stock to be achieved via the recycling/reclamation of existing refrigerants, a wide range of other assets will also be launched thanks to the 3R ECOSYSTEM. The now fully functional Retradeables marketplace will introduce a new win-win business model providing full transparency on acting parties, volumes and types of refrigerants, prices and

availability of refrigerants. After that, the innovative self-certification and self-declaration schemes will foster both the use of high-quality, cost-efficient recycled/reclaimed F-gases and the establishment of an accurate database of information to enable full traceability for F-gases recovered in the market (currently not available). At the same time, both a reliable legal framework and a registration system will be applied to verify, among other inputs, the F-gas licenses of ecosystem users so that fraud and piracy phenomena can be prevented.

Finally, it is worth pointing out that one of the main goals of the Retradeables project is to raise awareness among a total of 30,600 individuals during the demonstration phase and 222,600 individuals during the replication phase. This is supposed to be achieved through their participation in the project's dissemination and communication activities, as well as in the planned training campaigns. Overall, 250,000 individuals (installers/service companies and total amount of other stakeholders) are to be introduced to the circular economy of existing refrigerants, fully responding to the EU and global framework strategies for the transition of the HVAC-R industry to alternatives for managing F-gases, given their negative impact on global warming and climate change.

Regarding future work, two main research areas are proposed. The first research area is relevant to the inventory of the existing legislative frameworks in each EU member state regarding the management of used F-gases after their recovery. This necessity arises from the completely different implementation of the F-Gas Regulation by the EU member states [4,7], resulting in completely different practices per EU country in terms of the classification (or not) of used F-gases as waste after their recovery from HVAC-R equipment, change of ownership and transportation of recovered refrigerants. As part of the project tasks, the various legal barriers detected in the three demo countries (SK, HU, CZ) have already been mapped and efforts are being made, in cooperation with local authorities, to gradually eliminate them through the implementation of a standardised certification and training system. Certainly, similar legal barriers or gaps will exist in other EU countries as well. Therefore, they should first be identified as soon as possible and then a detailed roadmap should be drawn up for their elimination so that the circular approach can be effectively applied.

The second research area is relevant to the possible transfer of the project results to other sectors such as automotive air conditioning (A/C) and Waste Electrical & Electronic Equipment (WEEE). Specifically for the automotive sector, there is still a large stock of R134a to be recovered, as this was the liquid of choice for automotive A/C system manufacturers until 2017 when it was replaced by hydrofluoroolefin (HFO) refrigerant R1234yf under Directive 2006/40/EC (EU MAC Directive), which totally banned the use of F-gases with a GWP of more than 150 in all new vehicles placed on the EU market [28]. However, the real challenge seems to be WEEE, because it is not only a major source of residual F-gases but also one of the fastest growing waste streams in the EU. Considering these two facts above, the proper management of electrical and electronic equipment (EEE) after its lifetime is another key aspect of the relevant EU legislative framework. Based on Directive 2012/19/EU (EU WEEE Directive), special emphasis has been placed on the importance of the recovery and recycling of refrigerants injected into EEE, as they are a potential source of GHG emissions [29]. In this context, the circular economy ecosystem proposed by the Retradeables project can serve as powerful tool to add the tracking and trading of F-gases recovered by old or used electronic equipment on the European markets, thus benefiting the electronics industry, the EU and local governments, too. Proper separation by type of refrigerant in the various WEEE recycling plants across Europe is a prerequisite to enable subsequent recycling/reclamation rather than destruction. Therefore, the most common refrigerant separation practices applied in existing WEEE recycling plants in Europe should be investigated, as they are a critical factor in the respective range of recycling/recovery possibilities.

Author Contributions: Conceptualisation, N.B., S.K. and D.K.; methodology, N.B. and D.K.; validation, N.B.; investigation, N.B.; resources, S.K. and P.P.; data curation, P.P. and S.T.; writing—original draft preparation, S.T.; writing—review and editing, N.B. and P.P.; visualisation, S.T.; supervision, N.B. and S.K.; project administration, N.B., S.K. and P.P.; funding acquisition, N.B. and D.K. All authors have read and agreed to the published version of the manuscript.

Funding: This work was performed as one of the tasks of the Retradeables project, which is funded by the LIFE Programme of the European Union under grant agreement LIFE19 CCM/AT/001226–LIFE Retradeables. Expected start date: 1 July 2020; Expected end date: 30 June 2024.

Data Availability Statement: Much of the data presented in this study are available through the official project website: https://retradeables.com/. In addition, a number of deliverables recently produced under the Retradeables project are posted in the "Downloads" section of the website, providing interested parties with a variety of information relevant to the 3R ECOSYSTEM.

Conflicts of Interest: The authors declare no conflict of interest. It is also noted that the funders had no role in the design of the study; in the collection, analyses or interpretation of data; in the writing of the manuscript; or in the decision to publish the results.

Abbreviations

The following abbreviations are used in this manuscript:

CZ	Czech Republic
DACE	Daikin Central Europe
DENV	Daikin Europe N.V.
EC	European Commission
EU	European Union
F-gases	Fluorinated Gases
GHG	Greenhouse Gas
Gt	Gigatonnes
GWP	Global Warming Potential
HCFCs	Hydrochlorofluorocarbons
HFCs	Hydrofluorocarbons
HFOs	Hydrofluoroolefins
HU	Hungary
HVAC-R	Heating, Ventilation, Air Conditioning and Refrigeration
IoT	Internet of Things
KPI	Key Performance Indicator
Mt	Megatonnes
NTUA	National Technical University of Athens
POM	Placed On the Market
SK	Slovakia
WEEE	Waste Electrical & Electronic Equipment

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