Exploring the Role of U.K. Government Policy in Developing the University Entrepreneurial Finance Ecosystem for Cleantech

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***Abstract*—Vast sums of public money are invested into universities globally as anchor institutions and knowledge bases providing seedbed resources for research and development and entrepreneurship. Focusing on university science and technology research we examine two U.K. case studies of government support from the "Innovation Knowledge Centre" (IKC) program to translate research into industry innovation for public good. Although IKCs are not tasked to address climate change, the two case studies demonstrate tremendous potential for Cleantech development. An exploratory entrepreneurial finance ("entfin") ecosystem theoretical lens contextualizes the catalytic roles of universities and public funding to support industry at the base of the innovation finance escalator. We thus develop university-industry ecosystems literature, addressing the gap in nurturing university entfin for climate change. Our qualitative case study methodology includes literature review and 51 key informant interviews with: policymakers; university research leaders, technology transfer officers, specialist research to industry innovation "translation" staff, SME beneficiaries, trade bodies; and early-stage private finance providers. We reveal nuances in different emerging innovation sectors—notably their degree of maturity, locality, and outcome horizons for achieving impact, drawing attention to the key roles of universities and financing and their interactions within their entfin ecosystems. We demonstrate the need for government long horizon, deep pocket, investment, and integrated university entfin policy mix, alongside more open, inclusive, ecosystem development between different actors.**

***Index Terms*—Cleantech, entrepreneurial finance ecosystem, innovation, policy evaluation, science and technology, universities.**

I. Introduction

CLIMATE change is now the primary policy objective of many countries globally, as witnessed by COP26 (Glasgow, November 2021). As yet there is little evidence from the entrepreneurial finance ("entfin") or university ecosystems literature that examines the role of policy interventions to stimulate innovative clean technology ventures ("Cleantechs") to address climate change [1]. This article addresses this research gap [2] by examining U.K. policy relating to; first, the operation of university entfin ecosystems in supporting new science and technology (S&T) research translation into spin-out and small business innovations; second, how such innovations can contribute to developing Cleantechs that can impact on achieving Net Zero reductions in greenhouse gases by 2050 or sooner [2].

Universities are major anchor institutions [3] and knowledge bases [4] providing seedbed resources for research and development (R&D) and entrepreneurship. Globally, vast investments are made by governments into supporting university S&T and entrepreneurial teaching. This is expected to deliver public good through innovative spin-out companies, adoption of innovative practices in existing enterprises and creation of a more entrepreneurial and competitive local, regional, and national economy, thus leading to improved environments and living standards [5]. Recent studies demonstrate the need to understand the operation of entrepreneurial ecosystems [6] and the catalytic roles of universities within these [7], [8]. However, relatively few studies examine the vital contribution of public and private finance to facilitate "translation" of university-led R&D and entrepreneurship into impactful industry innovation [9]–[12]. Furthermore, within this article's U.K. research context, whilst the U.K. Government presents a so-called "world leader" clean growth strategy [13] there are no specific policies for addressing climate change through university-led Cleantech innovation. Here, taking our lead from Owen *et al.* [1] and Owen [14] in IEEE who call for greater research and policy attention to early-stage Cleantech innovation financing. "Cleantech" are here defined as typically young, early-stage ventures, which contribute product, service, and process innovations to lower carbon and greenhouse gas emissions and reduce (notably rare mineral) material use [15]. This article provides a unique insight into addressing the research question of how best to achieve university research translation into innovative Cleantech to achieve Net Zero.

We explore the role of the U.K. "Innovation Knowledge Centre" (IKC) program, which is tasked with public funding support to enable university-based emerging technology research translation into commercial industry innovation. We examine the processes of university translation of R&D into impactful industry innovation. This is achieved by combining university

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ecosystems theory [7] with the entfin escalator [16] to provide a university entfin ecosystem theoretical lens. This enables deeper insight into the interplay between different types of actors that contribute to the translation process [17]. In this respect, we adopt a qualitative case study of two U.K. IKCs at Imperial College and Cambridge University, entailing a literature review and 51 key informant interviews with: policymakers; university research leaders, technology transfer officers, specialist research to industry innovation "translation" staff, SME beneficiaries, trade bodies, and early-stage private finance providers. This article considers the central roles of university entrepreneurial teaching and R&D activities, and their interactions with private entrepreneurs and industry and public and private financiers. The focus is S&T, since numerous studies point to early financing gaps in the valley of death [18], [14], which contribute to the failure to commercialize university research and establish industry innovation. We find that most early-stage finance escalator studies focus on post spin-out seed finance and subsequent Series A commercializing finance [19]–[21], whilst few examine the financing and impacts from the start of the finance escalator at the base of the innovation funding pyramid [11], [22]–[24]. Furthermore, no studies have specifically considered the financing of university related Cleantech and their potential impacts on Net Zero.

The article proceeds with an explanation of the qualitative methodological approach taken, a contextual review of the key literature, an explanation of the university entfin ecosystem theory-driven framework of analysis, emerging themes, discussion of the article's contribution to the literature and practical implications for policy, conclusion and assessment of research limitations, and future research development.

II. Methodological Approach

A qualitative multisourced case study methodology was adopted [17], [25] to enable initial scoping of the subject and triangulation [26] verification of evidence from different sources [27], [28].

Our research question [29] was how best to achieve university research translation into innovative Cleantech to achieve Net Zero? This initially required an extensive structured literature review [30], [31] examining the university ecosystem and the related role of finance. A Scopus (the largest global academic paper search program) search revealed a burgeoning broad academic literature on ecosystems during the past decade, but with little focus on the roles of universities in the development of industry with relevance to the more mature economy entfin ecosystems found in the U.K. We, therefore, focused on papers from Western Europe, North America and more advanced Oceania-Pacific Rim markets. Of the 50 higher level most relevant papers (Association of Business Schools ("ABS") higher 3+ ratings) only 10 directly addressed university entfin ecosystem issues in the past decade. These were supplemented with recent grey policy and practice literature and selective university focused lower tier academic articles to ensure highly relevant contemporary thematic coverage. This helped shape understanding of the university entfin in terms of policy, practice, and academic theoretical approaches, whilst also demonstrating considerable knowledge gaps, particularly for Cleantech. This informed the qualitative interview topic guide (discussed below).

We adopted a qualitative case study approach [26] to enable a greater understanding of the translation processes taking place between university and industry and the roles of public and private finance actors within the entfin ecosystem. We purposively selected two out of six current U.K. IKC university translation and financing programs as case studies to provide in-depth process evidence of Cleantech innovation within two distinctive emerging sector technologies [32]. These were selected on the basis that they have potential impact on Cleantechs and have been operational sufficiently long (at least 7 years) to observe processes and outcomes. We also selected contrastingly different emerging technology sectors with climate change and regional ecosystem impact potential; Imperial College London's synthetic biology ("Synbio") "SynbiCITE" Research Centre, and Cambridge University's Centre for Smart Infrastructure and Construction ('CSIC'). These case studies were supplemented by interviews with other IKC managers, including at Southampton University's Biofilm and Queens University Belfast's digital security center. We also draw on case study interviews from Cambridge University's Maxwell Centre, which received complementary U.K. Research Partnership Investment Fund (UKRPIF) infrastructure funding program investment for S&T translation work with industry. Collectively, the selected 51 interviews (26 of which were directly associated with the 2 case study IKCs, Table I) offer data triangulation and external validation of processes studied [33].

Interviews were recorded, transcribed, and analyzed using qualitative case analysis [34] by two independent researchers to avoid interpretative bias. Interview data was systematically entered into excel spreadsheets under the topic guide themes and reviewed. Emerging themes were independently coded by the researchers and then agreed [35]. Additionally, our initial findings were triangulated [27] by available secondary data (e.g., program management reports, website, and U.K. Research and Investment (UKRI's) Research Fish program output data). Our initial findings were then tested in two follow-up online workshops with al 6 IKCs in summer 2021, providing additional data validation [33].

In further detail, qualitative research involved multiple stakeholders within the university entfin ecosystem, consisting of 51 interviews (40 online during COVID-19) with university research leaders, project delivery specialists, assisted SMEs and larger businesses, and other stakeholders (policy leaders, research partners, and intermediary trade body organizations and 15 early-stage U.K.-based public and private finance providers (see Table I). Topic guide, semistructured, interviews offered consistent approaches and also opportunity for flexible focus to explore what mattered most for particular respondents [27]. Topic guides for different stakeholder types and investors (see Annex 1) were derived from prior literature and scoping work (including IKC reports; Cambridge [36]) and explored themes regarding policy aims and the strategic objectives of S&T university knowledge transfer into industry innovation programs, their specific translation processes and the financing requirements and

TABLE I
BREAKDOWN OF CASE STUDY INTERVIEWS (2017–2021)

Interview type	**Number of interviews (51 of which 26 directly related to the 2 IKC case studies)**
5 leading UK S&T centres: Cambridge University (2), Imperial College, Southampton University, Queens University Belfast.	10 interviews with Program leaders, administrators and academic research leaders, including 6 interviews with the 2 IKC case studies
Interviews with IKC specialist university tech translation staff (including TTO staff)	8 interviews, including 4 interviews with the 2 IKC case studies
Interviews with IKC industry beneficiaries	8 interviews, including 6 relating to the 2 IKC case studies
Interviews with other university staff and relate industry sector specialists to the IKCs	10 interviews, including 8 relating to the 2 IKC case studies
Public/private UK cleantech funders, including: Low Carbon Innovation Fund, Energy Entrepreneurs Fund, Clean Growth Fund, Private VCs, British Venture Capital Association, Business Angels, Green Angel Syndicate, Myler Ventures, Cambridge University Seed Fund, Bethnal Green Accelerator, British Business Bank, UCL Business Ltd, Imperial Enterprise.	15 interviews, 2 directly related to the IKC case study universities

options for universities and early-stage Cleantech innovators. Drawing from policy evaluation literature, the approach sought to establish the IKC's Theory of Change (ToC) rationales and underpinning logic models for operation [37], activities and stakeholder engagement and outcomes, paying particular attention to evolutionary lessons learned and recommendations for program implementation and early-stage Cleantech financing improvement and measuring Net Zero impacts over time.

In summary, the adopted qualitative case study approach offered clear guidance on the current policy and practices of the U.K. university entfin ecosystem contextualized by academic theoretical literature for relevant mature global markets. It addressed a demonstrably clear gap in the literature for the early-stage, pre-seed university entfin ecosystem nurturing and development of Cleantech. This shaped the qualitative study and through adopting an entfin ecosystem theoretical lens it provided a series of emerging, tested themes for the future guidance of theory, policy and practice in this field.

III. LITERATURE AND POLICY CONTEXT

A. Context of U.K. Government S&T Programs

The U.K. is a major S&T research powerhouse within Europe. UKRI is a public agency with a budget of £7bn to invest in higher education and private industry research and innovation, with Innovate U.K. (IUK) operating as its private business funding arm—mainly through grants and loans. In further context, it may be estimated that the U.K. as a net receiver (15.5%) of European Union (EU) Horizon S&T funding could lose £1bn per year, from failure to participate in the Horizon 2020 funding stream (2021–2027) after U.K. exit from the EU. This represents 18 000 researcher posts. U.K. government policy interventions have ramped up in this field since Hauser's ([38], [39]) reports, the latter drawing on the early lessons of the IKC pilot program. Hauser ([38], p. 5) noted the following.

> *"The U.K. has a leading position in research, but it has long been acknowledged that it has not sufficiently capitalized on these strengths to capture economic benefit. This is in part down to a critical gap between research findings and outputs, and their development into commercial propositions." Hauser recommended U.K. government strategic choices to "…focus its attention on developing such a capability for platform technologies only where: there are large global markets worth billions of pounds per annum, the U.K. has technical leadership, there is a defensible technology position, and, there is capacity to anchor a significant part of the value chain, from research to manufacturing, in the U.K."*

With this in mind, university focused programs like the £900 m plus U.K. Research Partnership Investment Fund (UKRPIF, established 2012) and specifically £90 m plus IKCs (established in 2009) were developed to tackle typically earlier stage research translation in early emerging technology platforms, focusing mainly on technology readiness levels (TRLs) 3–6 taking feasible research to proven working pilots, but also spanning across to later commercialization TRLs 7–9. National specialist Catapult centers were also established from 2013 for nine broad strategic sector groups (including one addressing renewable energy), operating as independent centers bridging leading research institutions and industry to accelerate innovation commercialization, typically in more mature technologies at later TRL stages. A key role of such centers is to bring together a network of research, and support players, including collaborative and complementary research, supply chain and buyers, commercial skills, and financiers—taking a more holistic strategic ecosystem approach.

As a footnote to this introduction to contemporary U.K. Government University S&T policy, it is worth noting that the current U.K. Government Industrial Strategy [40] and related clean growth strategy [13] and more recently related green finance strategy [41] and Green Finance Institute, established in 2019 to oversee green finance and policy implementation, contain no direct policy for financing university-related Cleantech innovation. Rather, the Cleantech sectors developed in this article's IKC case studies have evolved as part of key technology platform developments. With this in mind, this article addresses an important issue in terms of how much further these Cleantech sectors might have developed with appropriate policy focus?

B. Literature Review of University S&T, the Entfin Context and Finance Gap

Our systematic literature review of ecosystem studies focusing on university S&T and the early stage entfin ecosystem (described above) identified two main strands of research: 1) evolution of the university ecosystem and 2) the role of entfin in developing the ecosystem. These two related strands are examined below. This review develops the SQW/CEEDR [43] study, which highlighted six key entrepreneurial ecosystem elements. We, therefore, contribute to ecosystem theory in terms of what are the key elements and actors of the system and their relative roles [42] specific to developing the university entfin ecosystem. The role of universities was just one (the others being leadership, infrastructure, business support, entrepreneurial finance, networking), by no means central element, as exemplified in Stam's [6] regional ecosystems approach. However, as Lerner [22] highlights, drawing from the innovation literature, universities and research institutions are a cornerstone of S&T research and innovation development. The question, therefore, addressed in this article is more specific than universities supporting entrepreneurship through teaching, which our literature review demonstrated is universally widespread [43]. It is about exploring the deeper translation processes, which are necessarily centered on university fundamental research activities and brings together wider elements of the ecosystem, including government policy and regulations, private finance, industry (in all forms from micro enterprises to corporate multinationals) and business support intermediaries—both financial and nonfinancial (e.g., trade bodies and think-tank policy lobbying groups). In this sense, a university entfin ecosystem theoretical lens provides a novel and appropriate approach.

Entrepreneurial finance is considered the life blood of new venture start-ups [43]. It covers any form of business finance [44], including innovation grants, bank debt (loans), crowd funding, or equity investment (e.g., from business angels and venture capitalists –"VCs"). Within more mature economies VC have evolved as key financial intermediaries generating organized pools of investment addressing early and growth stage venture requirements [45]. First established in the US in the 1950s [22], VC are a key element in the entrepreneurial ecosystem [46], potentially playing a crucial part in a cohesive finance escalator for university R&D and commercialization of innovative spin-outs [9]. However, a rapidly expanding contemporary entrepreneurial finance literature points to early-stage innovative venture private financing gaps and the need for public policy interventions [22], [19], [47]. Whilst these studies point to the liability of newness and smallness [48] of early-stage innovation ventures, few address the long horizon patient capital requirements of emerging S&T ventures. Yet, this appears to be the area of most private finance shortages [49], [1]) and very few studies examine the required entfin support around the initial university spin-out stage. Here, we need to develop the entfin information asymmetry ("IA") theory of Berger and Udell [50], whereby information opacity between ventures and investors reduces through the innovation and commercialization stages of the "finance escalator" [19], [16]. We need to explore how universities can reduce IA and increase investment through the operation of the university entfin ecosystem.

Munari *et al.* [11], [51] found that within Europe, combinations of proof of concept (PoC) grants and seed VC form the main government funded program approaches to directly addressing the private funding gaps, which affect early-stage university spin-outs, whilst Kochenkova *et al.* [52] also point to the growth of associated incubator and accelerator activities. However, these studies point to the complex policy mix [53] required to account for local and regional ecosystem specialisms and critical mass, knowledge spillovers, legal institutional frameworks, and pools of VC. One size fits all approaches are inadequate [23] with highly nuanced findings between types and locations of universities, relating to their quality tier, age, size, sector, and embedded corporate/investor linkages—notably, whether there is an established internal university seed VC fund. Higher tier universities' spin-outs appear more likely to obtain VC, with lower tier universities more effective when they perform an incubation function to help start-ups overcome their capital limitations [54]. However, these studies do not explain the range of activities and processes universities adopt in translating fundamental research ideas into a business backed by VC funds. They, therefore, point to the need for further university S&T entfin policy studies.

Theoretical and practical views as to what constitutes the university entrepreneurial finance ecosystem vary, but stress Triple Helix inclusivity [55] and a balance between universities, government support (regulation and policy) to facilitate innovation [3], private industry, and finance-related services [9]. Developing the soft network infrastructures of finance support services (accountants, lawyers, finance finding consultants) is also seen as crucial to VC development [22], whilst having the physical meeting place infrastructures, such as East London's night café structure to support young entrepreneurial meetings is seen as a vital component of London's Tech City [56]. Hayter [57] and Chesbrough [58] reviewed 117 spin-outs in five US metropolitan areas suggests a "nonlinear", network-centric perspective of spin-off success analogous to Chesbrough's [58], [59] Open Innovation paradigm. This evidence highlights the benefits of external sources of technology and management, alongside the industry experience of academic entrepreneurs, with an emphasis on inclusivity and open innovation approaches.

Such an embedded approach, which delivers a pipeline of investible university spin-outs is what private VC is attracted to and thrives on [60]. The success of the university financing ecosystem is complex, often requiring long-standing embedded VC and corporate ties [54] and public-private cofinancing [61].

University Technology Transfer Offices (TTOs) offer key anchor roles to negotiate university spin-out financing [51], [62], addressing IP rights and equity and royalty alignment with VCs and complex multiple angel and founder equity share arrangements. The more open and embedded culture of academics working with industry in Boston and San Francisco is perceived as advantageous in enabling university spin-out investment to thrive (Brandy *et al.*, 2015). However, crucially, Munari *et al.* [51] and BMG/CEEDR [24] also pointed to the need for university proof of concept and seed grants to be linked to VC for fluent next stage financing. These studies point to an emerging university entfin ecosystem theoretical framework, positioning the fundamental catalytic role of universities in S&T innovation and the need for a critical mass of activity (between ecosystem actors), which generates a convergence of innovative high-tech activity to attract private finance [63] and the roles of hard and soft infrastructure in terms of university lab facilities, coworking spaces and incubators (Florida and King, 2016), and also networking neighborhood cultures [56].

Focusing on university S&T, it is clear that universities perform two key services to private sector innovation, in addition to their more generalist entrepreneurship teaching and training role. First, they provide industry with fundamental research for adoption into industry innovation; second, they offer expertise and equipment for private sector R&D collaboration, which can take place in labs or on industry sites. The combination of these activities and the funding thereof, provide an essential springboard for new business innovation [38]. However, from an entfin information asymmetry theoretical perspective the problem of new emerging Cleantech innovation is challenging. Numerous studies point to the valley of death [18] of deep, long horizon, capital intensive, and expensive technology R&D innovations, which can take decades to commercialize. They highlight the public funding requirements to address market failures derived from the considerable time, expense, and uncertainties of such ventures [47]. The recent British Business Bank U.K. Equity Tracker report [64] highlighted this so-called "deeptech", patient capital funding problem. It suggested that although the U.K. has various government cofinancing programs (e.g., Enterprise Capital Fund, Angel Coinvestment Fund, Pandemic Future Fund, and Patient Capital Fund) to investment at successive stages of deeptech—from pre seed, through seed, venture commercialization, and scale up to achieve optimal investment exit—U.K. investment levels remain below those of the US market and demonstrate higher venture fall-out rates at each successive stage. The solution, as Owen *et al.* [1], [47], [65] repeatedly explored and indicated, is for a more cohesive, and notably better funded early-stage deeptech public-private finance escalator. However, what remains theoretically and practically understated in the literature is the processes that operate within the university entfin ecosystem that can reduce information asymmetries and result in effective financing of preseed new S&T "deeptech" ventures.

C. Creating a Research Framework for an Entfin Ecosystem Theoretical Lens

Further review of university ecosystem literature demonstrates that policy and theory has been developing input, process, and output models, which provide a theoretical framework for understanding the activities and outcomes of the university entfin ecosystem. These relate to: i) input measures such as research funding [66], with Graham [8] emphasizing S&T investment, including science parks, incubation and accelerator labs [67], [68], [69], and Graham [8] also emphasize the number of science and technology staff and graduates, notably post doc graduates, whilst Technology Transfer Officers [67] play a vital linking role to the industry ecosystem, alongside infrastructure and transport [42]. A further, nonfinancial factor proposed by Ranga *et al.* [70] related to the motivations and leadership of key players in the ecosystem. ii) Process measures lie at the heart of this article and often highlight the operation of TTOs, but also include the role of leadership and governance [42] and investment into collaborative industry grants/commercial funding, incubator and accelerator activities, patent, and high-quality policy and practice influencing publication production [8] , [69], [71]–[73]. Notably, there is considerable overlap and interlinking of processes across the model, for example entrepreneurship culture [42] can be seen as both an important antecedent and a key process and outcome. iii) Outcomes are what policymakers seek and stretch beyond the numbers of direct spin-out companies and university staff and students employed in S&T companies and their related job and GVA impacts [8], [69], [72]. Here, consideration needs to be given to the boundaries of the ecosystem [74], with studies including specific university cases Rissola [69] or European NUTS3 regions [75] and the timescales, since the full economic outcomes and their innovation cluster spillovers may take decades. This is certainly the case for emerging deeptech (requiring long horizon, capital expensive R&D), which form the focus of our study (Owen *et al.* [47]).

What emerges from these studies from an entfin ecosystem perspective is the need to understand the types of funding, processes and actor linkages involved in this embryonic stage of S&T deeptech venture creation and how these fit within the base of the innovation funding pyramid of the finance escalator [19]. This requires a research framework, which accounts for input investments, in terms of public funding and cofinancing programs, their approaches to the translation of research into industry R&D and the impacts of innovation. This needs to be suitably nuanced to control for specific sectors where industry investment structures may differ, depending on how well established; for example, life sciences have corporate pharma investors and seed to Series A hurdles that can be risk assessed, whilst new Cleantech platforms will not (Owen *et al.*, 2019) and the timelines to investment exits, which will vary from under five years for shorter horizon digitech, to potentially decades for longer horizon capital intensive deeptech [47].

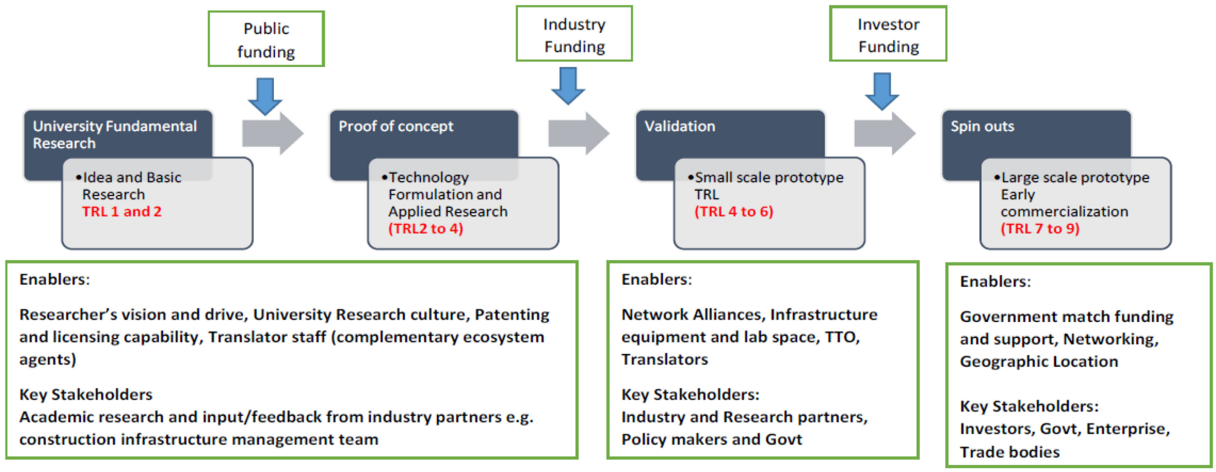

Fig. 1. Conceptualization of the university entfin framework.

Fig. 1 depicts the university entfin theoretical framework highlighting the actors and steps involved in converting fundamental research into a VC backed enterprise, through enabling enterprise innovation to overcome entfin information asymmetries. It also highlights the key enablers at each stage of the progression in Technology Readiness Levels (TRLs) that operate at the base of the funding pyramid, where the finance escalator ranges from preseed to seed and Series A early commercialization and progresses from public funded grants, through industry support finance (e.g., cofinancing labs, hosting trials) to private investor funding and public cofinancing programs (e.g., corporate accelerators, angels, seed VCs, and U.K. public VC e.g., Enterprise Capital Funds, and Seed/Enterprise Investment Scheme tax breaks). This framework informed the interview fieldwork design and data capture objectives to answer the research question how best to achieve university research translation into innovative Cleantech to achieve Net Zero?

IV. Findings

Initial findings borne out by our literature review and initial scoping interviews with IKC program managers and U.K. policymakers suggest that university fundamental research can play a critical catalytic role in developing globally leading cutting edge industry innovation with major jobs, export and local, regional, and national GVA potential. However, considerable barriers exist in the translation process spanning university fundamental research and industry innovation commercialization. These fundamentally relate to access to resources such as investment, equipment and skills, and communication leadership within specific institutional and ecosystem contexts. As such, the underlying ToC of the key U.K. programs (UKRPIF and IKC) is to focus public funding into universities with leading research expertise in emerging technologies to encourage industry innovation translation activities, which can lead to high potential scalable industry activities and attract private investment. Notably, sustainable Cleantech was not within the program remit, but is at the heart of our two IKC case studies (see Table II). Overall, key informant consensus suggested it is crucial to understand the processes undertaken and their context within U.K. regional and national entfin ecosystems, for "*…without sufficient finance [public and private], the U.K. will lose it global leading position…*" (IKC manager). There is also widespread acceptance for Lerner's (2010) proposition that public finance alone is not the solution and that a vibrant private seed finance market is required in order to balance public good with commercial acumen—a view supported in Owen's [14] review of the Innovate U.K. Investment Accelerator Program, which highlights the synergies of matching technical peer reviewed grants with commercial seed VC assessed funding.

Here, we examine in more depth the context and translation processes in two distinctively different emerging Cleantech sector markets addressed by IKCs; biotech (Imperial College synthetic biology center—"SynbiCITE") and construction infotech (CSIC)—to draw insights and lessons. The selection of these sector cases is necessarily limited by the range of IKC sector activity, but offers unique insights into the different translation processes that have evolved across both shorter and longer horizon technology and also at different technological maturity stages, factors, which prior entfin studies [1], [24], [49] suggest will impact on the availability of earlier stage private finance. For example, Owen [14] and Owen *et al.* [65] found that within the U.K. market longer horizon, higher capital intensive, investment sectors find it particularly difficult to attract earlier stage private investment. Further supporting evidence is also drawn from other IKCs (e.g., Southampton's National Biofilm Innovation Centre) and related UKRPIF program activity (e.g., for Cambridge Maxwell Centre and Imperial's Biofoundry). We should note the caveat that whilst outputs can be measured, the outcomes of early-stage deeptech innovation are still many years from being fully determined.

Drawing from university ecosystem theory [7], [43] and attending to the entfin preseed, early-stage funding theoretical gap, apparent from our literature review [47], [51] and initial key informant scoping, we utilize a hybrid university-entfin theoretical lens (see Fig. 1) to focus our analysis. Emergent themes are derived mainly from the two IKC case studies' related

TABLE II
COMPARISON OF SELECTED IKCS' ACTIVITIES BASED ON THE IDENTIFIED THEMES

IKC/Theme	**Imperial SynbiCITE** Est. 2013 synthetic biology ('synbio')	**Cambridge CSIC** Est. 2011 smart infrastructure
Funding	**Core IKC Funding: £12m** Other Public funding: £50m+ supported by £100m+ leveraged private funding	**Core IKC Funding: £14.9m** Private and Public Funding: £16.8m
Theory of Change	Develop emerging synbio tech platform through SME start-up launchpad/ accelerator to commercialize global health, sustainable solutions.	Adapting remote sensing and digital tech to transform new and existing infrastructure through smarter information working with industry to raise standards and adoption of more sustainable approaches.
Translation Ecosystem Themes		
Communication	Design and Facilities key staff alongside TTOs	Post Doc collaborative facilitation, Key staff industry connectivity
Accessibility	Bio design + facilities hub equipment access services – expanded by London White City Biofoundry (2017) Industry/research link/partners (60+), organize Synbitech - Europe's largest annual synbio trade event	Industry PoC demonstrator free service promotion and provision Workshops (online), exhibitions (eg ICE superheroes), conferences Partnership with Alan Turing Institute
Financing (projects)	PoC/pilot project funding (£400k) Business outreach hub, investor consortium, Rainbow seedfund £200k collaboration, industry club, House of Lords investor meetings £1m+ IKC investment: £1.6m+ co-finance	PoC demonstrator post doc projects Lab rental Private partner investment/grants (KTPs, EPSRC, IUK)
Skills & Management	4 Day MBA foundation program, lean launchpad accelerator, tech seminars	25 Secondments, industry collaboration, workshops, training
Leadership	Authored UK road map for synthetic biology; Founding partner – Global bio foundry association; Synbio event	Construction standards and policy documents; smart sustainability round table/Global Engineering Conference
Key Outputs (KPIs)	Assisted 80+ companies, 40+ intensive lab assists and 27+ PoCs plus 1 pilot grant 100+ MBA grads (7 universities) 2500+ event attendees	3 spin outs (Utterberry, Epsimom, 8Power) + Cemoptics (Skanska new division created) 62 formal partners 200+ PoC demonstrators
Outcomes	Development of UK-wide roadmap of 7 University network of synbio centres Directly assisted company valuations of over £1bn Contributed to c. 200 synbio SMEs/ West London cluster - 250+ jobs International collaborations with NUS Singapore, Berkeley, Stanford	33%+ material/time savings in infrastructure new build and reduced refurbishment National and international research collaborations including South Korean bridge infrastructure program Development of a carbon reduction code for the built environment Turing Institute big data energy use data
Climate change impacts	Improving biofuel efficiencies (e.g. biocrop engineering), bioremediation pollution removal and clean water e.g. Puraffinity's molecular filtration of PFA (synthetic polyfluoroalkyl) contaminated water. LabGenius spinout big data synthetic protein engineering platform ($30m investment) for health and material engineering. E.g. Airbus Industries material frame lightweight synbio applications.	One third reduction in cement for tunnel and concrete pile foundations (e.g. London CrossRail) – avoid over engineering. Improved infrastructure maintenance, reducing material input (e.g. Leeds viaduct) Contributing to the development of Cambridge smart city EV transport plans. Developed built enviro carbon reduction code Tackling energy poverty and use in India

interviews (see 51 in total, Table I) and supported by other stakeholders (e.g., early-stage investors).

Our findings are presented by five emerging themes (see Table II), all with ecosystem and financing implications and related output key performance indicators (KPIs)—which have been drawn from the in-depth qualitative interviews triangulated across program managers, key staff, treated industry beneficiaries, other industry (e.g., trade association) expert informants, and supporting evaluation data.

A. Communication Specialists (Industry Translators, Engineers, IP Agreements)

A key challenge is to bridge the communication barriers, which span between the academic aims and objectives of university researchers and the commercial needs of industry innovators. The IKCs enable the universities to recruit staff from industry backgrounds to provide a suitable conduit to translate fundamental research to meet industry requirements. These staff, such as software engineers, lab and project supervisors, and accelerator staff offer services that are distinctly different from the TTOs and IP licensing arrangements, which are often highlighted in the literature ([67], [72]).

A key role of the IKCs is to recruit and pay for key translation staff with appropriate understanding of the emerging platform technology and its potential industry application. At Imperial (SynbiCITE) this has been achieved through two key translator appointments; 1) a bio lab manager for projects, which implement automated workflows in collaborative projects with industry partners, bringing together academics with industry in lab conditions; 2) an analytics and metrology specialist to work with start-up and scale-up projects. For Cambridge (CSIC) the role of translation has involved a pioneering collaborative approach, requiring negotiating large construction industry project access agreements to test innovative IT remote sensing equipment, notably in infrastructure (road, rail—notably the recent national high-speed rail "HS2" and London underground CrossRail projects) and large-scale building and refurbishment projects. CSIC's managers explained that "*…the construction sector is traditional and has been a slow adopter of sensor technologies that are found for example in manufacturing processes and products*." Therefore, a considerable amount of IKC funding has gone into offering free post doc research time in order to demonstrate PoC and to obtain the in-kind key industry staff time input "…to work out what data is most critical for optimal practical industry impacts." In this case, CSIC drew heavily initially on the industry contacts of the IKC founding academic leaders, but also developed a critical role for a commercial academic specialist in fiber optics to develop ongoing contacts and opportunities for construction industry test projects.

Another notable IKC example is Queen's University Belfast's Centre for Secure IT (CSIT). Industry engagement was crucial to this IKC, which created two key posts; 1) an industry development manager and 2) a lab manager. The former promoting membership and access to CSIT's academic cyber security software libraries "…we needed to be industry engaged and led to solve their problems…" and the latter working in labs to support new software companies and products. CSIT also "quickly recognized that academics could not deliver the specialist translation required." They successfully applied for additional funding for 15 translation "engineers" with practical industry experience to operate on projects and in labs to assist member clients.

B. Accessibility to Equipment

Whilst IKC funding has not provided for lab building infrastructure, which is offered through the complementary UKRPIF, an important component has been the operation of innovation labs to facilitate translation. Access to lab space has not formed a large part of CSIC's program, since it has mainly been focused at taking existing later stage technology—described as "TRL 7-9 know-how demonstration" out to industry. However, companies use Cambridge University's labs, as in the case of the Maxwell Centre, which brings together physical materials science and engineering (c. £70m including £21m UKRPIF, established 2016), and colocate for short periods (typically 3–6 months), or hire temporary lab time to undertake research projects. The case of Silicon Microgravity (SMG) is instructive of the value of cross-cutting interdisciplinary labs in developing new industry innovation take-up. SMG came into contact with CSIC when it moved lab space to the civil engineering department. Previous focus had been on applying SMG's acceleration and gyro sensors for autonomous vehicles, but conversations with CSIC led to new customized industry leading applications for mapping buildings and underground pipes.

Imperial's IKC epitomizes the importance of "*…access to high value, state of the art equipment, which most SMEs would not be able to afford*." Respondents mentioned that the IKC initially offered very restricted access to lab space at the South Kensington campus, but their transfer to the £160m (including £50m from UKRPIF) West London multidisciplinary bioengineering campus enabled the establishment of White City Biofoundry with over £3m of contemporary cutting-edge equipment. They offer a full test cycle of works, from design of sequences, creation, assign systems, to analysis, with opportunities for industry to access hi-tech equipment, and address research questions. Lab space can be offered flexibly with around 15–20 companies annually using the lab's 6 bench spaces, alongside technical support which can come from post doc specialists (offered reportedly at circa "10% of real cost"). Clients are primarily SMEs and include Ph.D. students, with around 10 SMEs, typically pre revenue start-ups, receiving more intensive 3- to 6-month PoC support.

The value of Imperial's lab equipment services was highlighted by the CEO of LabGenius a spin-out from SynbiCITE. The IKC initially enabled postdoctoral studies through accessing an IUK grant, which enabled gene sequencing work. The company subsequently spun-out through Imperial Innovations (the university's specialist licensing and investment arm, renamed "Imperial Enterprise"), with no IP issues and subsequently raised $3 m in 2017 on the back of data supported by the IKC's £50k PoC grant funded work. Today, the company has $30m invested and continues to work with SynbiCITE. They now employ Imperial graduates and pay for lab space to test out Imperial's cutting-edge £500k equipment for long gene sequencing. This is the only research center in the U.K., where such work can be undertaken and offers companies the opportunity to test ideas and equipment, which they might then consider purchasing themselves. The CEO suggested that "SynbiCITE provided all the assistance required to start and develop our pioneering AI protein sequencing business and raise the funding required to do so. Without this support the business would never have started."

C. Financial Inducements (PoC, Free Trials/Demonstration Projects)

As alluded to above, financial support and inducement subsidies are crucial in the early-stage research translation phases addressed by the IKCs, at the stage when information asymmetries in new tech make ex ante investment decisions most difficult (Siegel *et al.* 2007). Munari *et al.* (2016) provide a unique study of the importance of PoC grants and the nature of their regional and national delivery, whilst Kochenkova *et al.* [52] found that they are often tied to incubator/accelerator and science park locational clusters and specialisms. The advantages of flexible PoC grant funding operated through the IKCs were mentioned by both Southampton (National Biofilm Centre) and Imperial (SynbiCITE) program managers as offering a flexible and relatively fast offer, when compared to the typically rigid timed calls and long review processes of national IUK programs. IKC PoC grants are promoted through high level university/industry networks nationally, with rapid peer review being undertaken by industry leading specialists. In the case of Imperial, most PoC grants have been allocated to London-based businesses that are able to locate in West London for launch pad accelerator support, working closely with the IKC industry translators. The introduction of SynbiCITE's four-day MBA course to selective universities such as Manchester as a foundation launchpad for PoC grants, has facilitated wider access, resulting in a couple of Manchester venture recipients. PoC grants of typically £50k tend to operate for short 3–6 months projects with Imperial offering circa 10 per year over the past three years. Specialist translation staff were quick to point to their work requiring wide ranging accelerator skills support to ensure that financial management, market research, and financial networking is in place to take the best cases to follow-on investment. In one case an extension grant of over £100k was offered for next stage pilot development work, but this was rare due to the lack of scale of IKC funding available. Overall, flexible funding, stage, and timing support had proven highly effective in gap funding for private market failure. "Only a couple of assisted companies have failed and collectively less than £400k of grants has assisted 27 companies to a current combined valuation of in excess of £800m!"

Cambridge CSIC has developed a different model. Program managers explained that the early part of the program involved persuading large industry corporates like Skanska, Costain, Arup, Mott Macdonald, and Jacobs to allow postdoctoral staff access to construction projects in order to pilot the use of fiber optic sensors in the construction process over periods of many months. It was noted for example that ground tests for London's CrossRail tunneling and building foundations required seasonal change coverage. This model offered free staff and equipment installation monitoring and analytics in order to test processes and refine systems and equipment for commercial adoption. The success of the approach can be gauged by the extent of U.K. industry take-up. For example, Skanska establishing a new "CemOptics" division devoted to industry leading use of fiber optics in concrete tunneling and pile foundations, estimated at saving over one third of materials costs due to improved understanding of seasonal ground stress testing. This also enabled a Ph.D. student project to spin out in 2013 into a successful business (Utterberry), which supplies customized micro sensors to construction projects.

D. Skills and Management Training (Courses, Accelerators)

All of the IKCs embed academic and industry training in their programs, demonstrating that the IKCs were funded by UKRI to develop academic teaching and published outputs as well as innovative industry outcomes.

Imperial's four-day rapid SynbiCITE MBA course aims to provide a grounding for synthetic biology graduates to learn about industry start-up opportunities and the required range of business administrative skills for spin-out start-ups. The course has become available to a high-level specialist university network in the U.K. (including Cambridge, Manchester, Bristol, Nottingham, Edinburgh) as a foundation course for entry into the SynbiCITE launchpad accelerator support, including training, access to lab equipment at Imperial's White City Biofoundry and PoC grant funding. SynbiCITE staff stress the importance of well-rounded business training: "Whilst we have a good pipeline of potential university spin-outs and start-up enquiries, many applicants with synbio skills lack business acumen, particularly in accessing markets, suppliers, management skills, and finance."

Cambridge CSIC IKC has evolved into many and various aspects of construction and infrastructure industry digital support services, ranging from fiber optic sensors aiding construction and whole of life infrastructure and buildings asset management to digital twinning for urban infrastructure planning. "CSIC's core agenda has been driven by a collaborative vision, creating solutions to industry … Sharing information, skills and knowledge …" To this effect conferences, workshops, secondments (over 25 to date), formal industry partnerships (60 plus to date) have formed a vital tailored approach to informing and then collaborating with a wide range of industry players including large construction companies, trade associations (e.g., British Geological Society) and small innovative start-ups, which can benefit from access to skilled one to one technical staff support, lab equipment, networking events, and business training workshops. The support structure was endorsed by the CEO of SMG (an early-stage SME innovator): "CSIC introduced key players within the construction industry … closely monitored our progress and offered support where necessary. This included lab testing for product development, enabling access to expensive instruments unaffordable for a start-up, access to research data and staff expertise in data modelling." Indeed, it appears that the only downside was that booking lab space during the Pandemic has been slow and bureaucratic. CSIC's impacts have only included three spin-outs in a sector that is dominated by large construction companies and their influence is perhaps better demonstrated by the 200 plus demonstrator/PoC projects undertaken, thus, far.

E. Leadership (Networking, Policy Regulation, Global Outreach)

A significant role and measure of the success of the IKCs is their leadership in the U.K. and globally within their respective emerging industrial sectors. This underscores the importance of taking an ecosystem view to understanding the catalytic, leading roles that the IKC's have in developing the institutional linkages and regulations required to build confidence and trust in emerging technology sectors and encourage industry adoption and private investment for early-stage innovation [11], [22], [46].

Here, Cambridge's CSIC IKC demonstrates what is required to drive evolutionary change within a traditional industry "*…it* *brought the idea to develop smart infrastructure in construction*." The IKC, established in 2011, built upon pre-existing research and industry linkages (in 2005 the team's fiber optics sensors assisted Channel Tunnel construction) within the U.K. and globally of leading team members. From the start the IKC held events with key trade bodies such as the Institute of Civil Engineers (ICE), leading to 2016 publication of ICE and Department for Transport best practice guides. In 2018, CSIC played a leading role internationally in the smart sustainability roundtable at the Global Engineering Conference and development of the Carbon Reduction Code for the Built Environment, currently being trialed by the U.K. Environment Agency. Industry experts point to CSIC's leading role in ICE steering groups on digital transformation, whilst international outreach is widespread, through close links with Berkeley University (where Professor Soga, a founder of CSIC is now based) and universities in South East Asia, leading to major contribution to South Korea's national bridge building program.

Imperial's IKC team had already established a U.K. (arguably global) leading position when after a decade of pioneering research, initially stimulated through meetings with MIT, they developed the national roadmap for U.K. synbio development, which formed the basis for the IKC's establishment in 2013. This sets out the catalytic role of national biofoundries for assisting innovative start-ups, with linkages to other regional synbio university and research specialists. This was recognized globally as a leading initiative, which others have followed and SynbiCITE recently established a global biofoundry networking group across 30 countries. Success has been based on considerable efforts to work with the U.K. government through All Party Parliamentary Groups to educate politicians and policymakers of the potential contribution the sector can make to climate change and economic growth. They also hold parliamentary promotions for international inward investment into the industry. SynbiCITE's leaders point to the enormous long term public investment required to develop synbio, with China ($400m) and the US ($100m) committing large sums into biofoundries and future commitments by these countries planned to run into the $billions. They reflect that ultimately "*…government requires a champion to ensure that sufficient investment is provided to maintain global leadership*."

F. Summary

Our findings (summarized in Table II) demonstrate that a significant amount of public funding, from a range of programs that bring together capital and revenue support is required in order to generate private funding leverage and deliver the desired industry innovation outcomes. The university ecosystem theoretical lens highlights different IKC process pathways and key elements to achieving outcomes. For example, CSIC adopted an outreach strategy of engaging with large construction industry companies in order to achieve market penetration for innovative variants of mature technology, whilst SynbiCITE focused on an incubation catalyst role for new venture start-ups to develop the new synbio tech platform. The addition of the entfin theoretical lens clarifies fundamental difference between the IKC case studies in technology maturity and deeptech characteristics, which appear largely influential on their private industry investment experiences. Cambridge CSIC's innovations are mainly later TRL (7–9) digital adaptations and large data management oriented, with large private sector customers able to subsume related hardware adoption costs, which then result (in the case of construction in clear and immediate cost-efficiency savings). Even in the case of longer-term property asset management, cost savings have been relatively quickly demonstrable (within a year of testing for seasonal effects). For Imperial SynbiCITE's earlier emerging synbio technology the rapid digital and AI driven technology side around TRL 3–6 has drawn huge investment into digital proofing, but a huge deeptech hardware financing gap exists—described as "*…at least 5x underfunded, compared to US investment markets*" by both Imperial and UCL's TTOs. Without substantial public and private investment many of the potentially game changing Cleantech outcomes, such as more efficient material use in manufacturing, will not be realized.

V. Discussion—Implications for University-Led Entfin Ecosystems and Cleantech Outcomes

The unique hybrid university entfin ecosystem theoretical lens applied to our analysis is very instructive in demonstrating the theoretical and practical contribution of this article. We progress university ecosystem [7], [43] theory by outlining, which elements of the ecosystem are most impactful. Critically, we also address the prior deficit in applying entfin theory to reveal the relationship between the university ecosystem elements and the processes which work well—particularly for Cleantech—and why this is the case, including drawing attention to deeptech funding requirements.

The widespread range of activities by the IKC case studies (Cambridge CSIC and Imperial SynbiCITE) across our five emerging themes (communication, accessibility, skills, leadership, and finance) underline the considerable requirement for public funding. They demonstrate the need for an entfin ecosystem approach [46]—particularly to draw attention to the requirements of early-stage Cleantech patient capital. It also highlights the anchor role [3] played by universities in developing new emerging technologies such as synbio and accelerating smart technology adoption in the construction sector. Our approach provides a synthesized enhancement on prior theoretical and practical work (notably SQW/CEEDR [43]) by demonstrating the key thematic elements in the entfin ecosystem that require attention, whilst also drawing out crucial differences in approaches, which have evolved over time to adjust to specific emerging technology sector nuances (such as the technology and applied industry level of maturity and purpose via adoption and development) and the spatial aspects of a university centered and led ecosystem, which may necessarily impact on the local/regional ecosystem, but also on wider national and international ecosystems. Above all, there is strong and uniformly supported evidence for the role of public funding to facilitate university research translation to industry innovation processes and to cofinance and work with private industry to ensure commercialization can take place. Here, we develop theory and practice by focusing on what this means in terms of establishing the most effective entfin ecosystem processes to generate public good and specifically Cleantech outcomes over time.

First, from a contextual perspective, applying a university entfin lens builds on theory by demonstrating that the preseed market requires a combination of public policy mix [51] and university ecosystem linkages to leverage sufficient scale public-private corporate finance for effective university research to industry innovation translation processes. We further use our hybrid theoretical lens to demonstrate that ecosystem collaboration between universities to deliver more efficient resource-cost allocation extends nationally and internationally (contributing a different element to Moortel and Crispeels [38], [76] strategic management framework). The IKCs only provide relatively small sums of catalytic funding for staff translation and associated network and outreach development activities. Whilst a key finding is that hiring industry experienced translators (who understand academic research and commercial requirements and can bridge the knowledge transfer gap between academia and industry) is essential to delivering industry innovation impact (Hauser [38], [39]), large-scale investment into state-of-the-art equipment and lab facilities (such as through UKRPIF) is also crucial and has to be kept up to date. Capital equipment costs are high for synbio and one way the national network of universities have proceeded is via niche specialisms (e.g., Imperial specialize in AI, whilst Manchester invest in robotics). This effectively shares costs, enhances regional niche specialist focus and key private industry partner investor linkages (encouraged by UKRPIF). This may be viewed as an effective policy mix [14], with regional economic gains (e.g., Manchester students participate in the Imperial MBA and create spinouts in the North of England), provided that the universities work as an effective national network. There is also scope for international collaborative working between universities, particularly to address Climate change, highlighted by Cambridge's work in India to deliver energy efficiency and alleviate energy poverty.

Our university entfin theoretical lens also offers advancement to overcoming information asymmetries in the preseed finance escalator [14]. From a baseline of the innovation investment pyramid perspective, the IKCs have developed very effective solutions, using a mix of PoC and accelerator approaches. A fundamental advantage of the IKC approach is to put the emphasis on the university specialist as the initial funding provider (rather than a national nonspecialist centralized funder approach), operating across national university networks in the case of Imperial and Southampton's biotech IKCs. These facilitate relatively rapid and tailored funding packages, which are supported by specialist industry facing IKC staff. In the case of Cambridge CSIC these offer project demonstration for big construction industry collaborators, whereas for Imperial these relate to technical PoC, access to state of the art testing equipment alongside rounded industry launch-pad support for management skills and next stage investment linkages. Here, we advance Munari et al's [52] university ecosystem theoretical discussion of regional and national impact. We find that a national program with regional university specialist research focus can have national and international outreach, which is nuanced by ecosystem factors relating specifically to complementary university networks, technology maturity (TRL levels), and industry financing mix.

A contribution of the university entfin ecosystem theoretical lens is the observation that emerging technology investment scale and commercialization horizons vary considerably and present different challenges to the early-stage innovation investment escalator [65]. Technology, which is software oriented such as cyber security (or synbio digital modeling) is typically shorter horizon, less capital intensive and more likely to be attractive to private investment. This is borne out by the relatively rapid development of commercial application by small and larger businesses in Belfast's cyber tech cluster (including 60 plus companies contributing £80m GVA). In contrast, whilst overhead costs for synbio and biofilm IP progression are reducing for entry level ICT equipment, leading to a largely grant and speculative private investor-led cluster of big data-led AI-driven ventures, there is little investment structure in place for the longer horizon deeptech, high-cost capital equipment investment required to develop commercial industry innovation. Currently, much of the £1bn valuation of Imperial's West London new venture synbio cluster is based on IP and patent potential. Without considerable U.K. government cofinancing investment (in-line with US and Chinese synbio investments of several hundred million dollars), U.K. prime mover leadership will be lost and many of these ventures will fail or suffer suboptimal trade sale exits to overseas companies. It was suggested by Imperial's IKC managers that a government VC cofund could catalyze considerable private funding into the sector, which currently lacks the private corporate investment funding found in the more mature risk-assessable biopharma sector.

Our hybrid theoretical lens also highlights the crucial connectivity between government cofunding to leverage private investment into university and preseed innovation and university leadership to raise policy and private funder awareness [14], [43]. Recent interviews with UCL and Imperial TTOs suggest that the British Business Bank's Patient Capital Fund is now investing earlier, into university seed funds to match fund private leveraged finance. However, the TTOs have limited faith in national government sufficiently funding this market (particularly after the COVID-19 financial crisis) and are increasingly looking to the deep pockets of philanthropists to follow the Harvard Wyss Institute's funding model. The TTOs state that they are keen to promote inward investment and require increased marketing budgets to promote their research and innovation on the global stage. For example, Imperial points to being a top ten global S&T university (although only one seventh of the scale of MIT). They state that "…more global promotion of U.K. top performing S&T universities is required", but found that recent £50 000 promotion of their Cleantech activities for COP26 stretched their budget.

An important observation of the research is the lack of U.K. Government investment directly into the foundations of the Cleantech innovation funding pyramid or escalator (Owen *et al.* 2020; Owen, 2021). Neither case study IKC had a specific remit to address climate change, but they both demonstrate far reaching applications for their technologies globally to reduce material use—through for example construction sector use of cement, or Airbus adoption of more efficient synbio materials in aircraft manufacture (see Table II). Another major contribution of synbio and biofilm is in vastly improved water purification techniques, which can enhance biodiversity as well as arable farming (for biofuel and methane reduction). As stated, The U.K. Government and governments globally should have greater consideration for funding and supporting Cleantech innovations, particularly in supporting deeptech through to commercialization.

Finally, industry leadership and networking are critical to raising awareness of the value of the emerging sector to the U.K. economy. All of the IKC managers refer to working with various government departments, political lobbying groups, and national committees to ensure that there is an improving policy mix, which includes national and international regulations and good practice in ‘frontier’ industries, which have been described as “the wild west” and in need of regulatory and technical guidance to ensure industry standards, which can impact globally. Here, all three IKCs play leading roles in global university research networks in their respective sectors. Crucially, the delivery of new innovations and enhanced industry standards has been shown to have huge potential impact for climate change, in saving material costs for construction and on world health, for example, playing an important role in the rapid deployment of Pandemic vaccines.

VI. Conclusion and Limitations of the Study

This is a unique study of the U.K. university entfin ecosystem, focusing on two distinctive emerging technologies developing through the research and industry interactions of two U.K. Government funded University IKCs. Our adoption of a novel hybrid university entfin ecosystem theoretical framework reveals for the first time the specific nuances of different emerging innovation sectors—notably their degree of maturity, locality, and outcome horizons for achieving impact, drawing attention to the key roles of universities and financing and their interactions within the wider entfin ecosystems (at local/regional, national, and international scales). We advance current theory and practice literature by highlighting five key themes (communication, access, finance, skills and management, and leadership) for university entfin ecosystem development to facilitate innovative industry commercialization. We also note the lack of specific U.K. Government policy to support early stage Cleantech innovation and financing—neither IKC case study had a specific Cleantech remit, but both make outstanding contributions to Climate change. Finally, our findings underline the need for government long horizon, deep pocket, investment, and support to leverage private investment globally. This is best supported by an integrated university and entrepreneurial finance policy mix, alongside more open, inclusive, ecosystem development between different actors—including university to university networks—nationally and internationally.

This article is necessarily limited by the time, scale and location of the research. The U.K. is just one, leading Cleantech S&T market and future studies will be able to consider the longer-term implications of the emerging technologies and their respective impacts on global Cleantech activities. This article provides a suitable theoretical framework for further qualitative investigation of the university entfin ecosystem and the key emerging factors, which contribute to its commercial innovation advancement. It comes too soon to make more substantive quantitative assessment as much of the Cleantech innovation is yet to be fully commercialized, but there are sufficient signs to indicate that there will be major climate change impacts provided that sufficient investment is found.

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Exploring the Role of U.K. Government Policy in Developing the University Entrepreneurial Finance Ecosystem for Cleantech

Robyn Owen and Lakshminarasimhan Vedanthachari

***Abstract*—Vast sums of public money are invested into universities globally as anchor institutions and knowledge bases providing seedbed resources for research and development and entrepreneurship. Focusing on university science and technology research we examine two U.K. case studies of government support from the "Innovation Knowledge Centre" (IKC) program to translate research into industry innovation for public good. Although IKCs are not tasked to address climate change, the two case studies demonstrate tremendous potential for Cleantech development. An exploratory entrepreneurial finance ("entfin") ecosystem theoretical lens contextualizes the catalytic roles of universities and public funding to support industry at the base of the innovation finance escalator. We thus develop university-industry ecosystems literature, addressing the gap in nurturing university entfin for climate change. Our qualitative case study methodology includes literature review and 51 key informant interviews with: policymakers; university research leaders, technology transfer officers, specialist research to industry innovation "translation" staff, SME beneficiaries, trade bodies; and early-stage private finance providers. We reveal nuances in different emerging innovation sectors—notably their degree of maturity, locality, and outcome horizons for achieving impact, drawing attention to the key roles of universities and financing and their interactions within their entfin ecosystems. We demonstrate the need for government long horizon, deep pocket, investment, and integrated university entfin policy mix, alongside more open, inclusive, ecosystem development between different actors.**

***Index Terms*—Cleantech, entrepreneurial finance ecosystem, innovation, policy evaluation, science and technology, universities.**

I. Introduction

CLIMATE change is now the primary policy objective of many countries globally, as witnessed by COP26 (Glasgow, November 2021). As yet there is little evidence from the entrepreneurial finance ("entfin") or university ecosystems literature that examines the role of policy interventions to stimulate innovative clean technology ventures ("Cleantechs") to address climate change [1]. This article addresses this research gap [2] by examining U.K. policy relating to; first, the operation of university entfin ecosystems in supporting new science and technology (S&T) research translation into spin-out and small business innovations; second, how such innovations can contribute to developing Cleantechs that can impact on achieving Net Zero reductions in greenhouse gases by 2050 or sooner [2].

Universities are major anchor institutions [3] and knowledge bases [4] providing seedbed resources for research and development (R&D) and entrepreneurship. Globally, vast investments are made by governments into supporting university S&T and entrepreneurial teaching. This is expected to deliver public good through innovative spin-out companies, adoption of innovative practices in existing enterprises and creation of a more entrepreneurial and competitive local, regional, and national economy, thus leading to improved environments and living standards [5]. Recent studies demonstrate the need to understand the operation of entrepreneurial ecosystems [6] and the catalytic roles of universities within these [7], [8]. However, relatively few studies examine the vital contribution of public and private finance to facilitate "translation" of university-led R&D and entrepreneurship into impactful industry innovation [9]–[12]. Furthermore, within this article's U.K. research context, whilst the U.K. Government presents a so-called "world leader" clean growth strategy [13] there are no specific policies for addressing climate change through university-led Cleantech innovation. Here, taking our lead from Owen *et al.* [1] and Owen [14] in IEEE who call for greater research and policy attention to early-stage Cleantech innovation financing. "Cleantech" are here defined as typically young, early-stage ventures, which contribute product, service, and process innovations to lower carbon and greenhouse gas emissions and reduce (notably rare mineral) material use [15]. This article provides a unique insight into addressing the research question of how best to achieve university research translation into innovative Cleantech to achieve Net Zero.

We explore the role of the U.K. "Innovation Knowledge Centre" (IKC) program, which is tasked with public funding support to enable university-based emerging technology research translation into commercial industry innovation. We examine the processes of university translation of R&D into impactful industry innovation. This is achieved by combining university

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ecosystems theory [7] with the entfin escalator [16] to provide a university entfin ecosystem theoretical lens. This enables deeper insight into the interplay between different types of actors that contribute to the translation process [17]. In this respect, we adopt a qualitative case study of two U.K. IKCs at Imperial College and Cambridge University, entailing a literature review and 51 key informant interviews with: policymakers; university research leaders, technology transfer officers, specialist research to industry innovation "translation" staff, SME beneficiaries, trade bodies, and early-stage private finance providers. This article considers the central roles of university entrepreneurial teaching and R&D activities, and their interactions with private entrepreneurs and industry and public and private financiers. The focus is S&T, since numerous studies point to early financing gaps in the valley of death [18], [14], which contribute to the failure to commercialize university research and establish industry innovation. We find that most early-stage finance escalator studies focus on post spin-out seed finance and subsequent Series A commercializing finance [19]–[21], whilst few examine the financing and impacts from the start of the finance escalator at the base of the innovation funding pyramid [11], [22]–[24]. Furthermore, no studies have specifically considered the financing of university related Cleantech and their potential impacts on Net Zero.

The article proceeds with an explanation of the qualitative methodological approach taken, a contextual review of the key literature, an explanation of the university entfin ecosystem theory-driven framework of analysis, emerging themes, discussion of the article's contribution to the literature and practical implications for policy, conclusion and assessment of research limitations, and future research development.

II. Methodological Approach

A qualitative multisourced case study methodology was adopted [17], [25] to enable initial scoping of the subject and triangulation [26] verification of evidence from different sources [27], [28].

Our research question [29] was how best to achieve university research translation into innovative Cleantech to achieve Net Zero? This initially required an extensive structured literature review [30], [31] examining the university ecosystem and the related role of finance. A Scopus (the largest global academic paper search program) search revealed a burgeoning broad academic literature on ecosystems during the past decade, but with little focus on the roles of universities in the development of industry with relevance to the more mature economy entfin ecosystems found in the U.K. We, therefore, focused on papers from Western Europe, North America and more advanced Oceania-Pacific Rim markets. Of the 50 higher level most relevant papers (Association of Business Schools ("ABS") higher 3+ ratings) only 10 directly addressed university entfin ecosystem issues in the past decade. These were supplemented with recent grey policy and practice literature and selective university focused lower tier academic articles to ensure highly relevant contemporary thematic coverage. This helped shape understanding of the university entfin in terms of policy, practice, and academic theoretical approaches, whilst also demonstrating considerable knowledge gaps, particularly for Cleantech. This informed the qualitative interview topic guide (discussed below).

We adopted a qualitative case study approach [26] to enable a greater understanding of the translation processes taking place between university and industry and the roles of public and private finance actors within the entfin ecosystem. We purposively selected two out of six current U.K. IKC university translation and financing programs as case studies to provide in-depth process evidence of Cleantech innovation within two distinctive emerging sector technologies [32]. These were selected on the basis that they have potential impact on Cleantechs and have been operational sufficiently long (at least 7 years) to observe processes and outcomes. We also selected contrastingly different emerging technology sectors with climate change and regional ecosystem impact potential; Imperial College London's synthetic biology ("Synbio") "SynbiCITE" Research Centre, and Cambridge University's Centre for Smart Infrastructure and Construction ('CSIC'). These case studies were supplemented by interviews with other IKC managers, including at Southampton University's Biofilm and Queens University Belfast's digital security center. We also draw on case study interviews from Cambridge University's Maxwell Centre, which received complementary U.K. Research Partnership Investment Fund (UKRPIF) infrastructure funding program investment for S&T translation work with industry. Collectively, the selected 51 interviews (26 of which were directly associated with the 2 case study IKCs, Table I) offer data triangulation and external validation of processes studied [33].

Interviews were recorded, transcribed, and analyzed using qualitative case analysis [34] by two independent researchers to avoid interpretative bias. Interview data was systematically entered into excel spreadsheets under the topic guide themes and reviewed. Emerging themes were independently coded by the researchers and then agreed [35]. Additionally, our initial findings were triangulated [27] by available secondary data (e.g., program management reports, website, and U.K. Research and Investment (UKRI's) Research Fish program output data). Our initial findings were then tested in two follow-up online workshops with al 6 IKCs in summer 2021, providing additional data validation [33].

In further detail, qualitative research involved multiple stakeholders within the university entfin ecosystem, consisting of 51 interviews (40 online during COVID-19) with university research leaders, project delivery specialists, assisted SMEs and larger businesses, and other stakeholders (policy leaders, research partners, and intermediary trade body organizations and 15 early-stage U.K.-based public and private finance providers (see Table I). Topic guide, semistructured, interviews offered consistent approaches and also opportunity for flexible focus to explore what mattered most for particular respondents [27]. Topic guides for different stakeholder types and investors (see Annex 1) were derived from prior literature and scoping work (including IKC reports; Cambridge [36]) and explored themes regarding policy aims and the strategic objectives of S&T university knowledge transfer into industry innovation programs, their specific translation processes and the financing requirements and

TABLE I
BREAKDOWN OF CASE STUDY INTERVIEWS (2017–2021)

Interview type	Number of interviews (51 of which 26 directly related to the 2 IKC case studies)
5 leading UK S&T centres: Cambridge University (2), Imperial College, Southampton University, Queens University Belfast.	10 interviews with Program leaders, administrators and academic research leaders, including 6 interviews with the 2 IKC case studies
Interviews with IKC specialist university tech translation staff (including TTO staff)	8 interviews, including 4 interviews with the 2 IKC case studies
Interviews with IKC industry beneficiaries	8 interviews, including 6 relating to the 2 IKC case studies
Interviews with other university staff and relate industry sector specialists to the IKCs	10 interviews, including 8 relating to the 2 IKC case studies
Public/private UK cleantech funders, including: Low Carbon Innovation Fund, Energy Entrepreneurs Fund, Clean Growth Fund, Private VCs, British Venture Capital Association, Business Angels, Green Angel Syndicate, Myler Ventures, Cambridge University Seed Fund, Bethnal Green Accelerator, British Business Bank, UCL Business Ltd, Imperial Enterprise.	15 interviews, 2 directly related to the IKC case study universities

options for universities and early-stage Cleantech innovators. Drawing from policy evaluation literature, the approach sought to establish the IKC's Theory of Change (ToC) rationales and underpinning logic models for operation [37], activities and stakeholder engagement and outcomes, paying particular attention to evolutionary lessons learned and recommendations for program implementation and early-stage Cleantech financing improvement and measuring Net Zero impacts over time.

In summary, the adopted qualitative case study approach offered clear guidance on the current policy and practices of the U.K. university entfin ecosystem contextualized by academic theoretical literature for relevant mature global markets. It addressed a demonstrably clear gap in the literature for the early-stage, pre-seed university entfin ecosystem nurturing and development of Cleantech. This shaped the qualitative study and through adopting an entfin ecosystem theoretical lens it provided a series of emerging, tested themes for the future guidance of theory, policy and practice in this field.

III. LITERATURE AND POLICY CONTEXT

A. *Context of U.K. Government S&T Programs*

The U.K. is a major S&T research powerhouse within Europe. UKRI is a public agency with a budget of £7bn to invest in higher education and private industry research and innovation, with Innovate U.K. (IUK) operating as its private business funding arm—mainly through grants and loans. In further context, it may be estimated that the U.K. as a net receiver (15.5%) of European Union (EU) Horizon S&T funding could lose £1bn per year, from failure to participate in the Horizon 2020 funding stream (2021–2027) after U.K. exit from the EU. This represents 18 000 researcher posts. U.K. government policy interventions have ramped up in this field since Hauser's ([38], [39]) reports, the latter drawing on the early lessons of the IKC pilot program. Hauser ([38], p. 5) noted the following.

> *"The U.K. has a leading position in research, but it has long been acknowledged that it has not sufficiently capitalized on these strengths to capture economic benefit. This is in part down to a critical gap between research findings and outputs, and their development into commercial propositions." Hauser recommended U.K. government strategic choices to "…focus its attention on developing such a capability for platform technologies only where: there are large global markets worth billions of pounds per annum, the U.K. has technical leadership, there is a defensible technology position, and, there is capacity to anchor a significant part of the value chain, from research to manufacturing, in the U.K."*

With this in mind, university focused programs like the £900 m plus U.K. Research Partnership Investment Fund (UKRPIF, established 2012) and specifically £90 m plus IKCs (established in 2009) were developed to tackle typically earlier stage research translation in early emerging technology platforms, focusing mainly on technology readiness levels (TRLs) 3–6 taking feasible research to proven working pilots, but also spanning across to later commercialization TRLs 7–9. National specialist Catapult centers were also established from 2013 for nine broad strategic sector groups (including one addressing renewable energy), operating as independent centers bridging leading research institutions and industry to accelerate innovation commercialization, typically in more mature technologies at later TRL stages. A key role of such centers is to bring together a network of research, and support players, including collaborative and complementary research, supply chain and buyers, commercial skills, and financiers—taking a more holistic strategic ecosystem approach.

As a footnote to this introduction to contemporary U.K. Government University S&T policy, it is worth noting that the current U.K. Government Industrial Strategy [40] and related clean growth strategy [13] and more recently related green finance strategy [41] and Green Finance Institute, established in 2019 to oversee green finance and policy implementation, contain no direct policy for financing university-related Cleantech innovation. Rather, the Cleantech sectors developed in this article's IKC case studies have evolved as part of key technology platform developments. With this in mind, this article addresses an important issue in terms of how much further these Cleantech sectors might have developed with appropriate policy focus?

B. Literature Review of University S&T, the Entfin Context and Finance Gap

Our systematic literature review of ecosystem studies focusing on university S&T and the early stage entfin ecosystem (described above) identified two main strands of research: 1) evolution of the university ecosystem and 2) the role of entfin in developing the ecosystem. These two related strands are examined below. This review develops the SQW/CEEDR [43] study, which highlighted six key entrepreneurial ecosystem elements. We, therefore, contribute to ecosystem theory in terms of what are the key elements and actors of the system and their relative roles [42] specific to developing the university entfin ecosystem. The role of universities was just one (the others being leadership, infrastructure, business support, entrepreneurial finance, networking), by no means central element, as exemplified in Stam's [6] regional ecosystems approach. However, as Lerner [22] highlights, drawing from the innovation literature, universities and research institutions are a cornerstone of S&T research and innovation development. The question, therefore, addressed in this article is more specific than universities supporting entrepreneurship through teaching, which our literature review demonstrated is universally widespread [43]. It is about exploring the deeper translation processes, which are necessarily centered on university fundamental research activities and brings together wider elements of the ecosystem, including government policy and regulations, private finance, industry (in all forms from micro enterprises to corporate multinationals) and business support intermediaries—both financial and nonfinancial (e.g., trade bodies and think-tank policy lobbying groups). In this sense, a university entfin ecosystem theoretical lens provides a novel and appropriate approach.

Entrepreneurial finance is considered the life blood of new venture start-ups [43]. It covers any form of business finance [44], including innovation grants, bank debt (loans), crowd funding, or equity investment (e.g., from business angels and venture capitalists –"VCs"). Within more mature economies VC have evolved as key financial intermediaries generating organized pools of investment addressing early and growth stage venture requirements [45]. First established in the US in the 1950s [22], VC are a key element in the entrepreneurial ecosystem [46], potentially playing a crucial part in a cohesive finance escalator for university R&D and commercialization of innovative spin-outs [9]. However, a rapidly expanding contemporary entrepreneurial finance literature points to early-stage innovative venture private financing gaps and the need for public policy interventions [22], [19], [47]. Whilst these studies point to the liability of newness and smallness [48] of early-stage innovation ventures, few address the long horizon patient capital requirements of emerging S&T ventures. Yet, this appears to be the area of most private finance shortages [49], [1]) and very few studies examine the required entfin support around the initial university spin-out stage. Here, we need to develop the entfin information asymmetry ("IA") theory of Berger and Udell [50], whereby information opacity between ventures and investors reduces through the innovation and commercialization stages of the "finance escalator" [19], [16]. We need to explore how universities can reduce IA and increase investment through the operation of the university entfin ecosystem.

Munari *et al.* [11], [51] found that within Europe, combinations of proof of concept (PoC) grants and seed VC form the main government funded program approaches to directly addressing the private funding gaps, which affect early-stage university spin-outs, whilst Kochenkova *et al.* [52] also point to the growth of associated incubator and accelerator activities. However, these studies point to the complex policy mix [53] required to account for local and regional ecosystem specialisms and critical mass, knowledge spillovers, legal institutional frameworks, and pools of VC. One size fits all approaches are inadequate [23] with highly nuanced findings between types and locations of universities, relating to their quality tier, age, size, sector, and embedded corporate/investor linkages—notably, whether there is an established internal university seed VC fund. Higher tier universities' spin-outs appear more likely to obtain VC, with lower tier universities more effective when they perform an incubation function to help start-ups overcome their capital limitations [54]. However, these studies do not explain the range of activities and processes universities adopt in translating fundamental research ideas into a business backed by VC funds. They, therefore, point to the need for further university S&T entfin policy studies.

Theoretical and practical views as to what constitutes the university entrepreneurial finance ecosystem vary, but stress Triple Helix inclusivity [55] and a balance between universities, government support (regulation and policy) to facilitate innovation [3], private industry, and finance-related services [9]. Developing the soft network infrastructures of finance support services (accountants, lawyers, finance finding consultants) is also seen as crucial to VC development [22], whilst having the physical meeting place infrastructures, such as East London's night café structure to support young entrepreneurial meetings is seen as a vital component of London's Tech City [56]. Hayter [57] and Chesbrough [58] reviewed 117 spin-outs in five US metropolitan areas suggests a "nonlinear", network-centric perspective of spin-off success analogous to Chesbrough's [58], [59] Open Innovation paradigm. This evidence highlights the benefits of external sources of technology and management, alongside the industry experience of academic entrepreneurs, with an emphasis on inclusivity and open innovation approaches.

Such an embedded approach, which delivers a pipeline of investible university spin-outs is what private VC is attracted to and thrives on [60]. The success of the university financing ecosystem is complex, often requiring long-standing embedded VC and corporate ties [54] and public-private cofinancing [61].

University Technology Transfer Offices (TTOs) offer key anchor roles to negotiate university spin-out financing [51], [62], addressing IP rights and equity and royalty alignment with VCs and complex multiple angel and founder equity share arrangements. The more open and embedded culture of academics working with industry in Boston and San Francisco is perceived as advantageous in enabling university spin-out investment to thrive (Brandy *et al.*, 2015). However, crucially, Munari *et al.* [51] and BMG/CEEDR [24] also pointed to the need for university proof of concept and seed grants to be linked to VC for fluent next stage financing. These studies point to an emerging university entfin ecosystem theoretical framework, positioning the fundamental catalytic role of universities in S&T innovation and the need for a critical mass of activity (between ecosystem actors), which generates a convergence of innovative high-tech activity to attract private finance [63] and the roles of hard and soft infrastructure in terms of university lab facilities, coworking spaces and incubators (Florida and King, 2016), and also networking neighborhood cultures [56].

Focusing on university S&T, it is clear that universities perform two key services to private sector innovation, in addition to their more generalist entrepreneurship teaching and training role. First, they provide industry with fundamental research for adoption into industry innovation; second, they offer expertise and equipment for private sector R&D collaboration, which can take place in labs or on industry sites. The combination of these activities and the funding thereof, provide an essential springboard for new business innovation [38]. However, from an entfin information asymmetry theoretical perspective the problem of new emerging Cleantech innovation is challenging. Numerous studies point to the valley of death [18] of deep, long horizon, capital intensive, and expensive technology R&D innovations, which can take decades to commercialize. They highlight the public funding requirements to address market failures derived from the considerable time, expense, and uncertainties of such ventures [47]. The recent British Business Bank U.K. Equity Tracker report [64] highlighted this so-called "deeptech", patient capital funding problem. It suggested that although the U.K. has various government cofinancing programs (e.g., Enterprise Capital Fund, Angel Coinvestment Fund, Pandemic Future Fund, and Patient Capital Fund) to investment at successive stages of deeptech—from pre seed, through seed, venture commercialization, and scale up to achieve optimal investment exit—U.K. investment levels remain below those of the US market and demonstrate higher venture fall-out rates at each successive stage. The solution, as Owen *et al.* [1], [47], [65] repeatedly explored and indicated, is for a more cohesive, and notably better funded early-stage deeptech public-private finance escalator. However, what remains theoretically and practically understated in the literature is the processes that operate within the university entfin ecosystem that can reduce information asymmetries and result in effective financing of preseed new S&T "deeptech" ventures.

C. Creating a Research Framework for an Entfin Ecosystem Theoretical Lens

Further review of university ecosystem literature demonstrates that policy and theory has been developing input, process, and output models, which provide a theoretical framework for understanding the activities and outcomes of the university entfin ecosystem. These relate to: i) input measures such as research funding [66], with Graham [8] emphasizing S&T investment, including science parks, incubation and accelerator labs [67], [68], [69], and Graham [8] also emphasize the number of science and technology staff and graduates, notably post doc graduates, whilst Technology Transfer Officers [67] play a vital linking role to the industry ecosystem, alongside infrastructure and transport [42]. A further, nonfinancial factor proposed by Ranga *et al.* [70] related to the motivations and leadership of key players in the ecosystem. ii) Process measures lie at the heart of this article and often highlight the operation of TTOs, but also include the role of leadership and governance [42] and investment into collaborative industry grants/commercial funding, incubator and accelerator activities, patent, and high-quality policy and practice influencing publication production [8] , [69], [71]–[73]. Notably, there is considerable overlap and interlinking of processes across the model, for example entrepreneurship culture [42] can be seen as both an important antecedent and a key process and outcome. iii) Outcomes are what policymakers seek and stretch beyond the numbers of direct spin-out companies and university staff and students employed in S&T companies and their related job and GVA impacts [8], [69], [72]. Here, consideration needs to be given to the boundaries of the ecosystem [74], with studies including specific university cases Rissola [69] or European NUTS3 regions [75] and the timescales, since the full economic outcomes and their innovation cluster spillovers may take decades. This is certainly the case for emerging deeptech (requiring long horizon, capital expensive R&D), which form the focus of our study (Owen *et al.* [47]).

What emerges from these studies from an entfin ecosystem perspective is the need to understand the types of funding, processes and actor linkages involved in this embryonic stage of S&T deeptech venture creation and how these fit within the base of the innovation funding pyramid of the finance escalator [19]. This requires a research framework, which accounts for input investments, in terms of public funding and cofinancing programs, their approaches to the translation of research into industry R&D and the impacts of innovation. This needs to be suitably nuanced to control for specific sectors where industry investment structures may differ, depending on how well established; for example, life sciences have corporate pharma investors and seed to Series A hurdles that can be risk assessed, whilst new Cleantech platforms will not (Owen *et al.*, 2019) and the timelines to investment exits, which will vary from under five years for shorter horizon digitech, to potentially decades for longer horizon capital intensive deeptech [47].

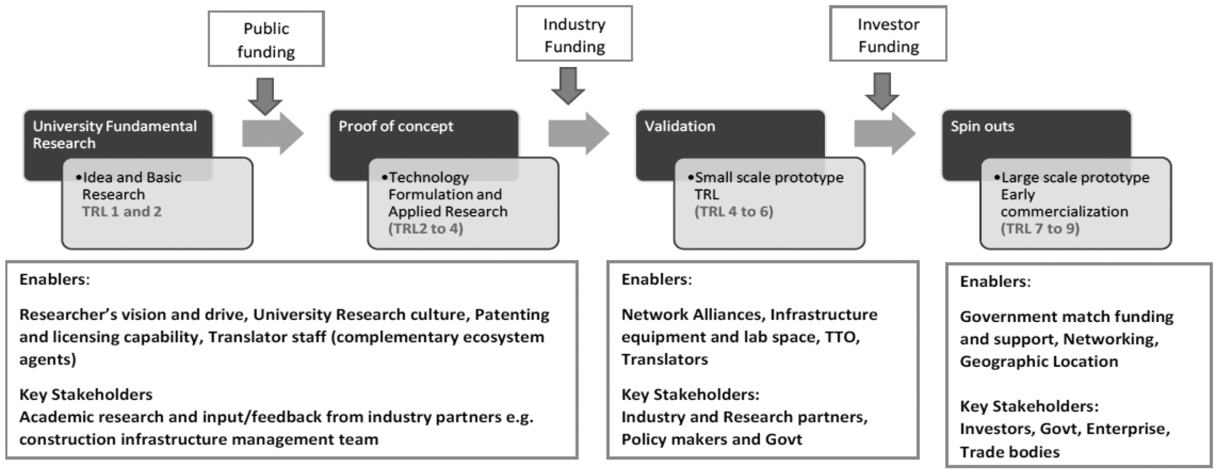

Fig. 1. Conceptualization of the university entfin framework.

Fig. 1 depicts the university entfin theoretical framework highlighting the actors and steps involved in converting fundamental research into a VC backed enterprise, through enabling enterprise innovation to overcome entfin information asymmetries. It also highlights the key enablers at each stage of the progression in Technology Readiness Levels (TRLs) that operate at the base of the funding pyramid, where the finance escalator ranges from preseed to seed and Series A early commercialization and progresses from public funded grants, through industry support finance (e.g., cofinancing labs, hosting trials) to private investor funding and public cofinancing programs (e.g., corporate accelerators, angels, seed VCs, and U.K. public VC e.g., Enterprise Capital Funds, and Seed/Enterprise Investment Scheme tax breaks). This framework informed the interview fieldwork design and data capture objectives to answer the research question how best to achieve university research translation into innovative Cleantech to achieve Net Zero?

IV. Findings

Initial findings borne out by our literature review and initial scoping interviews with IKC program managers and U.K. policymakers suggest that university fundamental research can play a critical catalytic role in developing globally leading cutting edge industry innovation with major jobs, export and local, regional, and national GVA potential. However, considerable barriers exist in the translation process spanning university fundamental research and industry innovation commercialization. These fundamentally relate to access to resources such as investment, equipment and skills, and communication leadership within specific institutional and ecosystem contexts. As such, the underlying ToC of the key U.K. programs (UKRPIF and IKC) is to focus public funding into universities with leading research expertise in emerging technologies to encourage industry innovation translation activities, which can lead to high potential scalable industry activities and attract private investment. Notably, sustainable Cleantech was not within the program remit, but is at the heart of our two IKC case studies (see Table II). Overall, key informant consensus suggested it is crucial to understand the processes undertaken and their context within U.K. regional and national entfin ecosystems, for "*…without sufficient finance [public and private], the U.K. will lose it global leading position…*" (IKC manager). There is also widespread acceptance for Lerner's (2010) proposition that public finance alone is not the solution and that a vibrant private seed finance market is required in order to balance public good with commercial acumen—a view supported in Owen's [14] review of the Innovate U.K. Investment Accelerator Program, which highlights the synergies of matching technical peer reviewed grants with commercial seed VC assessed funding.

Here, we examine in more depth the context and translation processes in two distinctively different emerging Cleantech sector markets addressed by IKCs; biotech (Imperial College synthetic biology center—"SynbiCITE") and construction infotech (CSIC)—to draw insights and lessons. The selection of these sector cases is necessarily limited by the range of IKC sector activity, but offers unique insights into the different translation processes that have evolved across both shorter and longer horizon technology and also at different technological maturity stages, factors, which prior entfin studies [1], [24], [49] suggest will impact on the availability of earlier stage private finance. For example, Owen [14] and Owen *et al.* [65] found that within the U.K. market longer horizon, higher capital intensive, investment sectors find it particularly difficult to attract earlier stage private investment. Further supporting evidence is also drawn from other IKCs (e.g., Southampton's National Biofilm Innovation Centre) and related UKRPIF program activity (e.g., for Cambridge Maxwell Centre and Imperial's Biofoundry). We should note the caveat that whilst outputs can be measured, the outcomes of early-stage deeptech innovation are still many years from being fully determined.

Drawing from university ecosystem theory [7], [43] and attending to the entfin preseed, early-stage funding theoretical gap, apparent from our literature review [47], [51] and initial key informant scoping, we utilize a hybrid university-entfin theoretical lens (see Fig. 1) to focus our analysis. Emergent themes are derived mainly from the two IKC case studies' related

TABLE II
COMPARISON OF SELECTED IKCS' ACTIVITIES BASED ON THE IDENTIFIED THEMES

IKC/Theme	**Imperial SynbiCITE** Est. 2013 synthetic biology ('synbio')	**Cambridge CSIC** Est. 2011 smart infrastructure
Funding	**Core IKC Funding: £12m** Other Public funding: £50m+ supported by £100m+ leveraged private funding	**Core IKC Funding: £14.9m** Private and Public Funding: £16.8m
Theory of Change	Develop emerging synbio tech platform through SME start-up launchpad/ accelerator to commercialize global health, sustainable solutions.	Adapting remote sensing and digital tech to transform new and existing infrastructure through smarter information working with industry to raise standards and adoption of more sustainable approaches.
Translation Ecosystem Themes		
Communication	Design and Facilities key staff alongside TTOs	Post Doc collaborative facilitation, Key staff industry connectivity
Accessibility	Bio design + facilities hub equipment access services – expanded by London White City Biofoundry (2017) Industry/research link/partners (60+), organize Synbitech - Europe's largest annual synbio trade event	Industry PoC demonstrator free service promotion and provision Workshops (online), exhibitions (eg ICE superheroes), conferences Partnership with Alan Turing Institute
Financing (projects)	PoC/pilot project funding (£400k) Business outreach hub, investor consortium, Rainbow seedfund £200k collaboration, industry club, House of Lords investor meetings £1m+ IKC investment: £1.6m+ co-finance	PoC demonstrator post doc projects Lab rental Private partner investment/grants (KTPs, EPSRC, IUK)
Skills & Management	4 Day MBA foundation program, lean launchpad accelerator, tech seminars	25 Secondments, industry collaboration, workshops, training
Leadership	Authored UK road map for synthetic biology; Founding partner – Global bio foundry association; Synbio event	Construction standards and policy documents; smart sustainability round table/Global Engineering Conference
Key Outputs (KPIs)	Assisted 80+ companies, 40+ intensive lab assists and 27+ PoCs plus 1 pilot grant 100+ MBA grads (7 universities) 2500+ event attendees	3 spin outs (Utterberry, Epsimom, 8Power) + Cemoptics (Skanska new division created) 62 formal partners 200+ PoC demonstrators
Outcomes	Development of UK-wide roadmap of 7 University network of synbio centres Directly assisted company valuations of over £1bn Contributed to c. 200 synbio SMEs/ West London cluster - 250+ jobs International collaborations with NUS Singapore, Berkeley, Stanford	33%+ material/time savings in infrastructure new build and reduced refurbishment National and international research collaborations including South Korean bridge infrastructure program Development of a carbon reduction code for the built environment Turing Institute big data energy use data
Climate change impacts	Improving biofuel efficiencies (e.g. biocrop engineering), bioremediation pollution removal and clean water e.g. Puraffinity's molecular filtration of PFA (synthetic polyfluoroalkyl) contaminated water. LabGenius spinout big data synthetic protein engineering platform ($30m investment) for health and material engineering. E.g. Airbus Industries material frame lightweight synbio applications.	One third reduction in cement for tunnel and concrete pile foundations (e.g. London CrossRail) – avoid over engineering. Improved infrastructure maintenance, reducing material input (e.g. Leeds viaduct) Contributing to the development of Cambridge smart city EV transport plans. Developed built enviro carbon reduction code Tackling energy poverty and use in India

interviews (see 51 in total, Table I) and supported by other stakeholders (e.g., early-stage investors).

Our findings are presented by five emerging themes (see Table II), all with ecosystem and financing implications and related output key performance indicators (KPIs)—which have been drawn from the in-depth qualitative interviews triangulated across program managers, key staff, treated industry beneficiaries, other industry (e.g., trade association) expert informants, and supporting evaluation data.

A. Communication Specialists (Industry Translators, Engineers, IP Agreements)

A key challenge is to bridge the communication barriers, which span between the academic aims and objectives of university researchers and the commercial needs of industry innovators. The IKCs enable the universities to recruit staff from industry backgrounds to provide a suitable conduit to translate fundamental research to meet industry requirements. These staff, such as software engineers, lab and project supervisors, and accelerator staff offer services that are distinctly different from the TTOs and IP licensing arrangements, which are often highlighted in the literature ([67], [72]).

A key role of the IKCs is to recruit and pay for key translation staff with appropriate understanding of the emerging platform technology and its potential industry application. At Imperial (SynbiCITE) this has been achieved through two key translator appointments; 1) a bio lab manager for projects, which implement automated workflows in collaborative projects with industry partners, bringing together academics with industry in lab conditions; 2) an analytics and metrology specialist to work with start-up and scale-up projects. For Cambridge (CSIC) the role of translation has involved a pioneering collaborative approach, requiring negotiating large construction industry project access agreements to test innovative IT remote sensing equipment, notably in infrastructure (road, rail—notably the recent national high-speed rail "HS2" and London underground CrossRail projects) and large-scale building and refurbishment projects. CSIC's managers explained that "*…the construction sector is traditional and has been a slow adopter of sensor technologies that are found for example in manufacturing processes and products*." Therefore, a considerable amount of IKC funding has gone into offering free post doc research time in order to demonstrate PoC and to obtain the in-kind key industry staff time input "…to work out what data is most critical for optimal practical industry impacts." In this case, CSIC drew heavily initially on the industry contacts of the IKC founding academic leaders, but also developed a critical role for a commercial academic specialist in fiber optics to develop ongoing contacts and opportunities for construction industry test projects.

Another notable IKC example is Queen's University Belfast's Centre for Secure IT (CSIT). Industry engagement was crucial to this IKC, which created two key posts; 1) an industry development manager and 2) a lab manager. The former promoting membership and access to CSIT's academic cyber security software libraries "…we needed to be industry engaged and led to solve their problems…" and the latter working in labs to support new software companies and products. CSIT also "quickly recognized that academics could not deliver the specialist translation required." They successfully applied for additional funding for 15 translation "engineers" with practical industry experience to operate on projects and in labs to assist member clients.

B. Accessibility to Equipment

Whilst IKC funding has not provided for lab building infrastructure, which is offered through the complementary UKRPIF, an important component has been the operation of innovation labs to facilitate translation. Access to lab space has not formed a large part of CSIC's program, since it has mainly been focused at taking existing later stage technology—described as "TRL 7-9 know-how demonstration" out to industry. However, companies use Cambridge University's labs, as in the case of the Maxwell Centre, which brings together physical materials science and engineering (c. £70m including £21m UKRPIF, established 2016), and colocate for short periods (typically 3–6 months), or hire temporary lab time to undertake research projects. The case of Silicon Microgravity (SMG) is instructive of the value of cross-cutting interdisciplinary labs in developing new industry innovation take-up. SMG came into contact with CSIC when it moved lab space to the civil engineering department. Previous focus had been on applying SMG's acceleration and gyro sensors for autonomous vehicles, but conversations with CSIC led to new customized industry leading applications for mapping buildings and underground pipes.

Imperial's IKC epitomizes the importance of "*…access to high value, state of the art equipment, which most SMEs would not be able to afford*." Respondents mentioned that the IKC initially offered very restricted access to lab space at the South Kensington campus, but their transfer to the £160m (including £50m from UKRPIF) West London multidisciplinary bioengineering campus enabled the establishment of White City Biofoundry with over £3m of contemporary cutting-edge equipment. They offer a full test cycle of works, from design of sequences, creation, assign systems, to analysis, with opportunities for industry to access hi-tech equipment, and address research questions. Lab space can be offered flexibly with around 15–20 companies annually using the lab's 6 bench spaces, alongside technical support which can come from post doc specialists (offered reportedly at circa "10% of real cost"). Clients are primarily SMEs and include Ph.D. students, with around 10 SMEs, typically pre revenue start-ups, receiving more intensive 3- to 6-month PoC support.

The value of Imperial's lab equipment services was highlighted by the CEO of LabGenius a spin-out from SynbiCITE. The IKC initially enabled postdoctoral studies through accessing an IUK grant, which enabled gene sequencing work. The company subsequently spun-out through Imperial Innovations (the university's specialist licensing and investment arm, renamed "Imperial Enterprise"), with no IP issues and subsequently raised $3 m in 2017 on the back of data supported by the IKC's £50k PoC grant funded work. Today, the company has $30m invested and continues to work with SynbiCITE. They now employ Imperial graduates and pay for lab space to test out Imperial's cutting-edge £500k equipment for long gene sequencing. This is the only research center in the U.K., where such work can be undertaken and offers companies the opportunity to test ideas and equipment, which they might then consider purchasing themselves. The CEO suggested that "SynbiCITE provided all the assistance required to start and develop our pioneering AI protein sequencing business and raise the funding required to do so. Without this support the business would never have started."

C. Financial Inducements (PoC, Free Trials/Demonstration Projects)

As alluded to above, financial support and inducement subsidies are crucial in the early-stage research translation phases addressed by the IKCs, at the stage when information asymmetries in new tech make ex ante investment decisions most difficult (Siegel *et al.* 2007). Munari *et al.* (2016) provide a unique study of the importance of PoC grants and the nature of their regional and national delivery, whilst Kochenkova *et al.* [52] found that they are often tied to incubator/accelerator and science park locational clusters and specialisms. The advantages of flexible PoC grant funding operated through the IKCs were mentioned by both Southampton (National Biofilm Centre) and Imperial (SynbiCITE) program managers as offering a flexible and relatively fast offer, when compared to the typically rigid timed calls and long review processes of national IUK programs. IKC PoC grants are promoted through high level university/industry networks nationally, with rapid peer review being undertaken by industry leading specialists. In the case of Imperial, most PoC grants have been allocated to London-based businesses that are able to locate in West London for launch pad accelerator support, working closely with the IKC industry translators. The introduction of SynbiCITE's four-day MBA course to selective universities such as Manchester as a foundation launchpad for PoC grants, has facilitated wider access, resulting in a couple of Manchester venture recipients. PoC grants of typically £50k tend to operate for short 3–6 months projects with Imperial offering circa 10 per year over the past three years. Specialist translation staff were quick to point to their work requiring wide ranging accelerator skills support to ensure that financial management, market research, and financial networking is in place to take the best cases to follow-on investment. In one case an extension grant of over £100k was offered for next stage pilot development work, but this was rare due to the lack of scale of IKC funding available. Overall, flexible funding, stage, and timing support had proven highly effective in gap funding for private market failure. "Only a couple of assisted companies have failed and collectively less than £400k of grants has assisted 27 companies to a current combined valuation of in excess of £800m!"

Cambridge CSIC has developed a different model. Program managers explained that the early part of the program involved persuading large industry corporates like Skanska, Costain, Arup, Mott Macdonald, and Jacobs to allow postdoctoral staff access to construction projects in order to pilot the use of fiber optic sensors in the construction process over periods of many months. It was noted for example that ground tests for London's CrossRail tunneling and building foundations required seasonal change coverage. This model offered free staff and equipment installation monitoring and analytics in order to test processes and refine systems and equipment for commercial adoption. The success of the approach can be gauged by the extent of U.K. industry take-up. For example, Skanska establishing a new "CemOptics" division devoted to industry leading use of fiber optics in concrete tunneling and pile foundations, estimated at saving over one third of materials costs due to improved understanding of seasonal ground stress testing. This also enabled a Ph.D. student project to spin out in 2013 into a successful business (Utterberry), which supplies customized micro sensors to construction projects.

D. Skills and Management Training (Courses, Accelerators)

All of the IKCs embed academic and industry training in their programs, demonstrating that the IKCs were funded by UKRI to develop academic teaching and published outputs as well as innovative industry outcomes.

Imperial's four-day rapid SynbiCITE MBA course aims to provide a grounding for synthetic biology graduates to learn about industry start-up opportunities and the required range of business administrative skills for spin-out start-ups. The course has become available to a high-level specialist university network in the U.K. (including Cambridge, Manchester, Bristol, Nottingham, Edinburgh) as a foundation course for entry into the SynbiCITE launchpad accelerator support, including training, access to lab equipment at Imperial's White City Biofoundry and PoC grant funding. SynbiCITE staff stress the importance of well-rounded business training: "Whilst we have a good pipeline of potential university spin-outs and start-up enquiries, many applicants with synbio skills lack business acumen, particularly in accessing markets, suppliers, management skills, and finance."

Cambridge CSIC IKC has evolved into many and various aspects of construction and infrastructure industry digital support services, ranging from fiber optic sensors aiding construction and whole of life infrastructure and buildings asset management to digital twinning for urban infrastructure planning. "CSIC's core agenda has been driven by a collaborative vision, creating solutions to industry … Sharing information, skills and knowledge …" To this effect conferences, workshops, secondments (over 25 to date), formal industry partnerships (60 plus to date) have formed a vital tailored approach to informing and then collaborating with a wide range of industry players including large construction companies, trade associations (e.g., British Geological Society) and small innovative start-ups, which can benefit from access to skilled one to one technical staff support, lab equipment, networking events, and business training workshops. The support structure was endorsed by the CEO of SMG (an early-stage SME innovator): "CSIC introduced key players within the construction industry … closely monitored our progress and offered support where necessary. This included lab testing for product development, enabling access to expensive instruments unaffordable for a start-up, access to research data and staff expertise in data modelling." Indeed, it appears that the only downside was that booking lab space during the Pandemic has been slow and bureaucratic. CSIC's impacts have only included three spin-outs in a sector that is dominated by large construction companies and their influence is perhaps better demonstrated by the 200 plus demonstrator/PoC projects undertaken, thus, far.

E. Leadership (Networking, Policy Regulation, Global Outreach)

A significant role and measure of the success of the IKCs is their leadership in the U.K. and globally within their respective emerging industrial sectors. This underscores the importance of taking an ecosystem view to understanding the catalytic, leading roles that the IKC's have in developing the institutional linkages and regulations required to build confidence and trust in emerging technology sectors and encourage industry adoption and private investment for early-stage innovation [11], [22], [46].

Here, Cambridge's CSIC IKC demonstrates what is required to drive evolutionary change within a traditional industry "*…it* *brought the idea to develop smart infrastructure in construction*." The IKC, established in 2011, built upon pre-existing research and industry linkages (in 2005 the team's fiber optics sensors assisted Channel Tunnel construction) within the U.K. and globally of leading team members. From the start the IKC held events with key trade bodies such as the Institute of Civil Engineers (ICE), leading to 2016 publication of ICE and Department for Transport best practice guides. In 2018, CSIC played a leading role internationally in the smart sustainability roundtable at the Global Engineering Conference and development of the Carbon Reduction Code for the Built Environment, currently being trialed by the U.K. Environment Agency. Industry experts point to CSIC's leading role in ICE steering groups on digital transformation, whilst international outreach is widespread, through close links with Berkeley University (where Professor Soga, a founder of CSIC is now based) and universities in South East Asia, leading to major contribution to South Korea's national bridge building program.

Imperial's IKC team had already established a U.K. (arguably global) leading position when after a decade of pioneering research, initially stimulated through meetings with MIT, they developed the national roadmap for U.K. synbio development, which formed the basis for the IKC's establishment in 2013. This sets out the catalytic role of national biofoundries for assisting innovative start-ups, with linkages to other regional synbio university and research specialists. This was recognized globally as a leading initiative, which others have followed and SynbiCITE recently established a global biofoundry networking group across 30 countries. Success has been based on considerable efforts to work with the U.K. government through All Party Parliamentary Groups to educate politicians and policymakers of the potential contribution the sector can make to climate change and economic growth. They also hold parliamentary promotions for international inward investment into the industry. SynbiCITE's leaders point to the enormous long term public investment required to develop synbio, with China ($400m) and the US ($100m) committing large sums into biofoundries and future commitments by these countries planned to run into the $billions. They reflect that ultimately "*…government requires a champion to ensure that sufficient investment is provided to maintain global leadership*."

F. Summary

Our findings (summarized in Table II) demonstrate that a significant amount of public funding, from a range of programs that bring together capital and revenue support is required in order to generate private funding leverage and deliver the desired industry innovation outcomes. The university ecosystem theoretical lens highlights different IKC process pathways and key elements to achieving outcomes. For example, CSIC adopted an outreach strategy of engaging with large construction industry companies in order to achieve market penetration for innovative variants of mature technology, whilst SynbiCITE focused on an incubation catalyst role for new venture start-ups to develop the new synbio tech platform. The addition of the entfin theoretical lens clarifies fundamental difference between the IKC case studies in technology maturity and deeptech characteristics, which appear largely influential on their private industry investment experiences. Cambridge CSIC's innovations are mainly later TRL (7–9) digital adaptations and large data management oriented, with large private sector customers able to subsume related hardware adoption costs, which then result (in the case of construction in clear and immediate cost-efficiency savings). Even in the case of longer-term property asset management, cost savings have been relatively quickly demonstrable (within a year of testing for seasonal effects). For Imperial SynbiCITE's earlier emerging synbio technology the rapid digital and AI driven technology side around TRL 3–6 has drawn huge investment into digital proofing, but a huge deeptech hardware financing gap exists—described as "*…at least 5x underfunded, compared to US investment markets*" by both Imperial and UCL's TTOs. Without substantial public and private investment many of the potentially game changing Cleantech outcomes, such as more efficient material use in manufacturing, will not be realized.

V. Discussion—Implications for University-Led Entfin Ecosystems and Cleantech Outcomes

The unique hybrid university entfin ecosystem theoretical lens applied to our analysis is very instructive in demonstrating the theoretical and practical contribution of this article. We progress university ecosystem [7], [43] theory by outlining, which elements of the ecosystem are most impactful. Critically, we also address the prior deficit in applying entfin theory to reveal the relationship between the university ecosystem elements and the processes which work well—particularly for Cleantech—and why this is the case, including drawing attention to deeptech funding requirements.

The widespread range of activities by the IKC case studies (Cambridge CSIC and Imperial SynbiCITE) across our five emerging themes (communication, accessibility, skills, leadership, and finance) underline the considerable requirement for public funding. They demonstrate the need for an entfin ecosystem approach [46]—particularly to draw attention to the requirements of early-stage Cleantech patient capital. It also highlights the anchor role [3] played by universities in developing new emerging technologies such as synbio and accelerating smart technology adoption in the construction sector. Our approach provides a synthesized enhancement on prior theoretical and practical work (notably SQW/CEEDR [43]) by demonstrating the key thematic elements in the entfin ecosystem that require attention, whilst also drawing out crucial differences in approaches, which have evolved over time to adjust to specific emerging technology sector nuances (such as the technology and applied industry level of maturity and purpose via adoption and development) and the spatial aspects of a university centered and led ecosystem, which may necessarily impact on the local/regional ecosystem, but also on wider national and international ecosystems. Above all, there is strong and uniformly supported evidence for the role of public funding to facilitate university research translation to industry innovation processes and to cofinance and work with private industry to ensure commercialization can take place. Here, we develop theory and practice by focusing on what this means in terms of establishing the most effective entfin ecosystem processes to generate public good and specifically Cleantech outcomes over time.

First, from a contextual perspective, applying a university entfin lens builds on theory by demonstrating that the preseed market requires a combination of public policy mix [51] and university ecosystem linkages to leverage sufficient scale public-private corporate finance for effective university research to industry innovation translation processes. We further use our hybrid theoretical lens to demonstrate that ecosystem collaboration between universities to deliver more efficient resource-cost allocation extends nationally and internationally (contributing a different element to Moortel and Crispeels [38], [76] strategic management framework). The IKCs only provide relatively small sums of catalytic funding for staff translation and associated network and outreach development activities. Whilst a key finding is that hiring industry experienced translators (who understand academic research and commercial requirements and can bridge the knowledge transfer gap between academia and industry) is essential to delivering industry innovation impact (Hauser [38], [39]), large-scale investment into state-of-the-art equipment and lab facilities (such as through UKRPIF) is also crucial and has to be kept up to date. Capital equipment costs are high for synbio and one way the national network of universities have proceeded is via niche specialisms (e.g., Imperial specialize in AI, whilst Manchester invest in robotics). This effectively shares costs, enhances regional niche specialist focus and key private industry partner investor linkages (encouraged by UKRPIF). This may be viewed as an effective policy mix [14], with regional economic gains (e.g., Manchester students participate in the Imperial MBA and create spinouts in the North of England), provided that the universities work as an effective national network. There is also scope for international collaborative working between universities, particularly to address Climate change, highlighted by Cambridge's work in India to deliver energy efficiency and alleviate energy poverty.

Our university entfin theoretical lens also offers advancement to overcoming information asymmetries in the preseed finance escalator [14]. From a baseline of the innovation investment pyramid perspective, the IKCs have developed very effective solutions, using a mix of PoC and accelerator approaches. A fundamental advantage of the IKC approach is to put the emphasis on the university specialist as the initial funding provider (rather than a national nonspecialist centralized funder approach), operating across national university networks in the case of Imperial and Southampton's biotech IKCs. These facilitate relatively rapid and tailored funding packages, which are supported by specialist industry facing IKC staff. In the case of Cambridge CSIC these offer project demonstration for big construction industry collaborators, whereas for Imperial these relate to technical PoC, access to state of the art testing equipment alongside rounded industry launch-pad support for management skills and next stage investment linkages. Here, we advance Munari et al's [52] university ecosystem theoretical discussion of regional and national impact. We find that a national program with regional university specialist research focus can have national and international outreach, which is nuanced by ecosystem factors relating specifically to complementary university networks, technology maturity (TRL levels), and industry financing mix.

A contribution of the university entfin ecosystem theoretical lens is the observation that emerging technology investment scale and commercialization horizons vary considerably and present different challenges to the early-stage innovation investment escalator [65]. Technology, which is software oriented such as cyber security (or synbio digital modeling) is typically shorter horizon, less capital intensive and more likely to be attractive to private investment. This is borne out by the relatively rapid development of commercial application by small and larger businesses in Belfast's cyber tech cluster (including 60 plus companies contributing £80m GVA). In contrast, whilst overhead costs for synbio and biofilm IP progression are reducing for entry level ICT equipment, leading to a largely grant and speculative private investor-led cluster of big data-led AI-driven ventures, there is little investment structure in place for the longer horizon deeptech, high-cost capital equipment investment required to develop commercial industry innovation. Currently, much of the £1bn valuation of Imperial's West London new venture synbio cluster is based on IP and patent potential. Without considerable U.K. government cofinancing investment (in-line with US and Chinese synbio investments of several hundred million dollars), U.K. prime mover leadership will be lost and many of these ventures will fail or suffer suboptimal trade sale exits to overseas companies. It was suggested by Imperial's IKC managers that a government VC cofund could catalyze considerable private funding into the sector, which currently lacks the private corporate investment funding found in the more mature risk-assessable biopharma sector.

Our hybrid theoretical lens also highlights the crucial connectivity between government cofunding to leverage private investment into university and preseed innovation and university leadership to raise policy and private funder awareness [14], [43]. Recent interviews with UCL and Imperial TTOs suggest that the British Business Bank's Patient Capital Fund is now investing earlier, into university seed funds to match fund private leveraged finance. However, the TTOs have limited faith in national government sufficiently funding this market (particularly after the COVID-19 financial crisis) and are increasingly looking to the deep pockets of philanthropists to follow the Harvard Wyss Institute's funding model. The TTOs state that they are keen to promote inward investment and require increased marketing budgets to promote their research and innovation on the global stage. For example, Imperial points to being a top ten global S&T university (although only one seventh of the scale of MIT). They state that "…more global promotion of U.K. top performing S&T universities is required", but found that recent £50 000 promotion of their Cleantech activities for COP26 stretched their budget.

An important observation of the research is the lack of U.K. Government investment directly into the foundations of the Cleantech innovation funding pyramid or escalator (Owen *et al.* 2020; Owen, 2021). Neither case study IKC had a specific remit to address climate change, but they both demonstrate far reaching applications for their technologies globally to reduce material use—through for example construction sector use of cement, or Airbus adoption of more efficient synbio materials in aircraft manufacture (see Table II). Another major contribution of synbio and biofilm is in vastly improved water purification techniques, which can enhance biodiversity as well as arable farming (for biofuel and methane reduction). As stated, The U.K. Government and governments globally should have greater consideration for funding and supporting Cleantech innovations, particularly in supporting deeptech through to commercialization.

Finally, industry leadership and networking are critical to raising awareness of the value of the emerging sector to the U.K. economy. All of the IKC managers refer to working with various government departments, political lobbying groups, and national committees to ensure that there is an improving policy mix, which includes national and international regulations and good practice in 'frontier' industries, which have been described as "the wild west" and in need of regulatory and technical guidance to ensure industry standards, which can impact globally. Here, all three IKCs play leading roles in global university research networks in their respective sectors. Crucially, the delivery of new innovations and enhanced industry standards has been shown to have huge potential impact for climate change, in saving material costs for construction and on world health, for example, playing an important role in the rapid deployment of Pandemic vaccines.

VI. Conclusion and Limitations of the Study

This is a unique study of the U.K. university entfin ecosystem, focusing on two distinctive emerging technologies developing through the research and industry interactions of two U.K. Government funded University IKCs. Our adoption of a novel hybrid university entfin ecosystem theoretical framework reveals for the first time the specific nuances of different emerging innovation sectors—notably their degree of maturity, locality, and outcome horizons for achieving impact, drawing attention to the key roles of universities and financing and their interactions within the wider entfin ecosystems (at local/regional, national, and international scales). We advance current theory and practice literature by highlighting five key themes (communication, access, finance, skills and management, and leadership) for university entfin ecosystem development to facilitate innovative industry commercialization. We also note the lack of specific U.K. Government policy to support early stage Cleantech innovation and financing—neither IKC case study had a specific Cleantech remit, but both make outstanding contributions to Climate change. Finally, our findings underline the need for government long horizon, deep pocket, investment, and support to leverage private investment globally. This is best supported by an integrated university and entrepreneurial finance policy mix, alongside more open, inclusive, ecosystem development between different actors—including university to university networks—nationally and internationally.

This article is necessarily limited by the time, scale and location of the research. The U.K. is just one, leading Cleantech S&T market and future studies will be able to consider the longer-term implications of the emerging technologies and their respective impacts on global Cleantech activities. This article provides a suitable theoretical framework for further qualitative investigation of the university entfin ecosystem and the key emerging factors, which contribute to its commercial innovation advancement. It comes too soon to make more substantive quantitative assessment as much of the Cleantech innovation is yet to be fully commercialized, but there are sufficient signs to indicate that there will be major climate change impacts provided that sufficient investment is found.

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