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'Salvation and profit': deconstructing the clean-tech bubble

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ABSTRACT
From 2004 to 2008, a bubble formed in clean technologies, such as solar, biofuels, batteries and other renewable energy sources. In this paper, we analyse this clean-tech bubble through the lens of the Social Bubble Hypothesis, which holds that bubbles can accelerate technological innovation. We synthesise the development of the clean-tech bubble, its history, and the role of venture capital and government funding in catalysing it, and present evidence that the clean-tech bubble constituted an example of an innovation-accelerating process.

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1. Introduction

On 8 March 2007, legendary venture capitalist John Doerr, who has invested in Netscape, Amazon and Google, gave a talk entitled 'Salvation (and Profits) in Greentech'. In his talk, Doerr described climate change as 'the largest economic opportunity of the 21st century, and a moral imperative' (2007). The title of Doerr's talk perfectly encapsulates the simultaneous belief in profits and salvation that fuelled the clean-tech bubble, which, a year later, spectacularly crashed. In this paper, we analyse the clean-tech bubble and address the question whether the clean-tech bubble developed the virtue of having accelerated innovation in clean and renewable energy technologies.

In order to tackle such questions, we draw on the Social Bubble Hypothesis, which holds that, under specific conditions and designs, speculative bubbles can be important components in the process of innovation (Sornette 2008; Gisler and Sornette 2009, 2010; Gisler, Sornette, and Woodard 2011; Huber and Sornette 2022).

In the economics and finance literature, speculative financial bubbles are considered to have predominately destructive social and economic effects. However, the formation of certain bubbles can act as important catalysts for socio-technological innovation. As they accelerate capital spending cycles that stimulate over-investment in infrastructures or emerging technologies, some bubbles have in the past enhanced economic productivity (for historical examples: Nairn 2002).

After the bust of the dot-com bubble, this bubble formed as private and public investors started to envision clean tech as the next frontier for technological innovation. Within the framework of social bubbles, the crucial question that needs to be addressed is to what degree the clean-tech bubble has really been accelerating innovation in clean technologies.

The paper is organised as follows. The first section provides a brief history of the clean-tech bubble. We then present a quantitative analysis of the bubble. We analyse in more detail

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VC investments in clean-tech and identify the challenges that arise for investments in this sector. In the next section, we analyse the clean-tech bubble through the lens of the Social Bubble Hypothesis. We conclude by providing in the last part of the paper a discussion of bubbles as innovation-accelerators and address the question whether the bubble catalysed technological innovation and adoption of clean technologies.

2. The clean-tech bubble: a short history

After the collapse of the dot-com bubble in 2000, which destroyed around USD 5 trillion in (previously excessively accumulated) market capitalisation, venture capital investors searching for new investment opportunities—started to envision clean-tech as the next frontier of technological innovation. Venture capital, however, was not the only factor driving the build-up of the clean-tech bubble.

At the start of the twenty-first century, debates about climate change intensified, and investing and developing green energy sources was becoming for many a moral imperative 'to save the Planet'. Not only was there an increasing inflow of venture capital, but the federal government started also to invest in emerging clean technologies. In 2005, as part of the Energy Policy Act, a federal loan guarantee programme was authorised at USD 4 billion. In 2007, the US Congress established, with USD 400 million in funding, the Advanced Research Projects-Energy (ARPA-E), which was modelled on DARPA—the agency that was instrumental in funding the development of the Internet (Bonvillian and Van Atta 2011). An additional USD 2.1 billion was invested by the US government through tax credits. Federal subsidies for renewable energy increased from USD 5.1 billion to USD 14.7 billion between 2007 and 2010. The USD 787 billion federal stimulus package, which was enacted in 2009 in response to the global financial crisis, included USD 79 billion for renewable and clean energy.

These massive government subsidies, in turn, fuelled VC investments. Whereas clean-tech investment amounted to a few hundred million dollars in 2005, in the following year, VCs invested USD 1.75 billion. Although clean-tech does not resemble the software investments that have been dominating VCs portfolios, investors compared solar, biofuels and batteries to the capital-intensive semiconductor and biotech industries. As Doerr remarked: 'Internet-sized markets are in the billions of dollars; the energy markets are in the trillions' (Doerr 2007). In 2009, at the peak of the bubble, VCs invested USD 4.9 billion into 356 alternative energy deals. Whereas VC investments in solar increased from USD 32 million in 2004 to USD 1.85 billion in 2008, venture investments in batteries increased 30-fold during this period (Eilperin 2012; Hargadon and Kenney 2012; Gaddy et al. 2017).

VC investments in clean-tech assumed increasing fossil fuel prices, in particular, natural gas. However, a confluence of factors, such as the financial crisis of 2008 that made it more challenging for VCs to raise capital, the decline in natural gas and oil prices, a drop in the prices of processed silicon, technological advances in natural gas extraction from shale, and overproduction in solar panel manufacturing, triggered the bust of the clean-tech bubble in 2008. One of the most dominant factors was the decline in natural gas and oil prices, which we will analyse in more detail below. Technical advances in natural gas extraction, such as hydraulic fracking, resulted in a collapse of natural gas prices. Another factor that contributed to the bust of the clean-tech bubble was the overproduction of processed silicon that resulted in a substantial decrease in silicon prices. This price-decrease, in turn, lowered costs and barriers to entry for other solar panel manufacturers (see Yergin 2011).

In 2008, the clean-tech bubble went bust. The Renewable Energy Industrial Index (RENIXX), which tracks the largest companies by market capitalisation in the renewable energy sector, crashed and cumulatively lost 64%. As a consequence of the bursting of the bubble, VC investments decreased from USD 4.1 billion in 2008 to USD 2.5 billion in 2009.

Investors started to realise that clean or renewable technologies represent a 'complex, established legacy sector' (Bonvillian and Weiss 2009). In other words, clean-tech did not satisfy the

conditions for massive venture capital financing to successfully accelerate radical technological breakthroughs. These conditions consist of (i) rapidly growing markets, (ii) scalable technology and startups, and (iii) large returns and rapid exits (that is, private and public market liquidity) (Hargadon and Kenney 2012). VCs assumed that clean-tech constitutes a rapidly growing market. In reality, the energy sector is characterised by high barriers to entry and high-capital costs, which constraints the rapid growth and diffusion of emerging clean technologies. Federal subsidies and investments in clean energy created artificial market growth and reduced investor risk-aversion. Furthermore, technology and startup scalability are difficult due to the need for long time horizons and for high capital intensity of 'hardware'-dominated clean-tech projects. The larger time scales that clean-tech requires make it, in turn, difficult for investors to achieve rapid exits. In essence, high scaling costs and the challenge for clean-tech startups to generate outsized growth in returns and market share—which VC investors need for raising their funds—make the clean energy sector difficult to invest in for VCs (Gaddy et al. 2017). ARPA-E's innovation-policy model played also a critical role in the clean-tech bubble. In contrast to DARPA, ARPA-E's policy resulted in the concentrated funding of selected high-risk/ high-reward startups. It specifically subsidised specific technologies, which, in turn, resulted in reduced competition between emerging technologies (Bonvillian and Weiss 2009). In other words, ARPA-E's policies created selected and overfunded potential winners, which raised barriers to entry for other clean-tech startups.

Before examining the social dynamics underlying the clean-tech bubble through the lens of the Social Bubble Hypothesis, we will in the next section provide quantitative analysis to size up the clean-tech bubble.

3. Quantitative analysis of the clean-tech bubble

3.1. Super-exponential growth and log-periodic power law singularity as diagnostic of bubbles

A statistical signature of financial bubbles is the existence of 'acceleration' (Ardila-Alvarez, Forró, and Sornette 2021)—i.e. increasing momentum—whichleads to super-exponential price growth (Sornette and Cauwels 2015). The pattern of faster-than-exponential (power law hyperbolic) price growth—which is fuelled by positive feedbacks on the growth rate of an asset's price by the price, return, and other financial and economic variables—makes bubbles detectable, in particular through log-periodic power law singularity (LPPLS) patterns (Johansen et al. 1999; Johansen and Sornette (2010); Sornette 2017; Sornette and Johansen 2001; Sornette and Zhou 2006; Jiang et al. 2010). This signature of positive feedback loops, which are characteristic for bubble regimes, can be quantitatively identified in a time series by a faster-than-exponential power law component, and by the existence of an increasing amplitude of low frequency volatility, which occurs either in isolation or simultaneously with varying relative importance. Mathematically, such bubble regimes of unsustainable growth can be identified by power law finite-time singular growth that is decorated by oscillations in the logarithm of time. The mathematical representation is obtained as the expansion of the Log-Periodic Power-Law Singularity (LPPLS) model for the expectation of the log price:

$$E[\ln p(t)] = A + B|t_c - t|^m + C|t_c - t|^m \cos(\omega \ln|t_c - t| + \phi), \tag{1}$$

where $P(t)$ is the price of the asset, t is time, t_c is the most probable time at which the bubble ends, $E[.]$ represents the expectation operator and A, B, C, f, m and ω are parameters defining the nonlinear equation. The exponent $0 < m < 1$ quantifies the strength of the super-exponential acceleration. The log-periodic angular frequency ω controls the discrete scaling structure of the accelerating bursts of volatility accompanying the development of the bubble (Sornette 1998).

3.2. Quantifying the clean-tech bubble: a LPPLS analysis

Applying the LPPLS model (1) to the Renewable Energy Industrial Index (RENIXX), we can detect a regime of super-exponential growth in the RENIXX from August 2004 to December 2007 (see Figure 1).

The start time t_1 of the interval from August 2004 to December 2007, over which the calibration of Equation (1) is performed, is selected using the method of Demos and Sornette (2019). The end time t_2 of this interval is selected between the two last largest peaks of the RENIXX index. As can be seen in Figure 1, the RENIXX index exhibits a regime of accelerating price corrections and rebounds—which are a defining characteristic of bubbles—that are driven by self-reinforcing feedback loops of herding behaviour (Sornette 2017). The price trajectory of the RENIXX becomes unsustainable and crashes between 2008 and 2009. The best LPPLS fit shown in Figure 1 is extrapolated beyond t_2, showing a correct timing of the transition from bubble to drawdown. It is important to recall that the LPPLS model describes the end of a bubble as a regime shift, which can often extend over several weeks or months.

Within the theory of financial bubbles and their subsequent regime change, which is used here, it was the unsustainability of the price growth itself that was the ultimate cause of the bursting of the clean-tech bubble. Now, as a speculative bubble is often influenced by developments occurring concomitantly in other markets, we now quickly test in the next sections how the global stock market and, in particular, the price of oil has affected the clean-tech bubble.

3.3. The clean-tech bubble and the stock market

Expanding on Figures 1 and 2 exemplifies to what extent the RENIXX went through a bubble from 2005 to 2008.

During 2007, the RENIXX almost continuously increased. It increased by 107.3%, reaching a high of 1918 points on December 28, 2007. In 2008, the index started to rise again by 35% to reach a second peak in June 2008 of 1652. This peak was followed by a drawdown of 58% in the second half of 2008. As this crash of the RENIXX overlaps with the time period of the bursting of the real

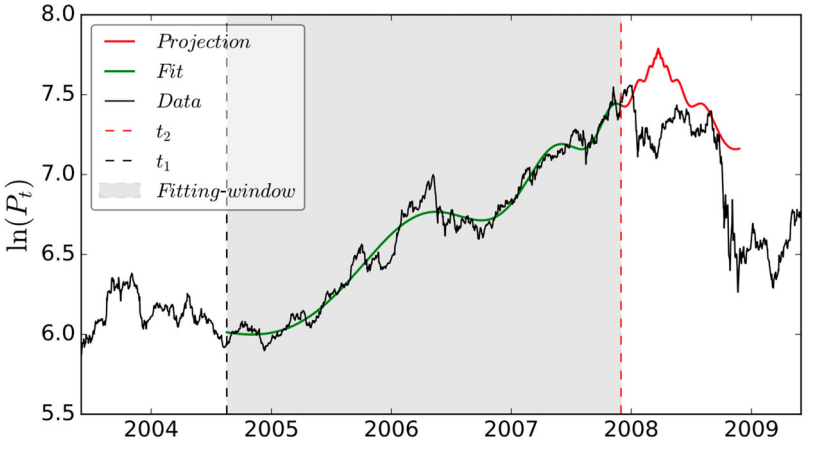

Figure 1. RENIXX daily prices in a logarithmic scale from 2003 to 2009. The oscillating continuous green line corresponds to the calibration of equation (1) (with the expansion of the cosine as $C\cos[w\ln(t_c - t) + f] = C_1\cos[w\ln(t_c - t)]\cos[f] - C_2\sin[w\ln(t_c - t)]\sin[f]$, where $C_1 = C\cos[f]$ and $C_2 = -C\sin[f]$, as proposed by Filimonov and Sornette (2013)) to the RENIXX with the parameters: $t_c = 113.5$, $A = 2.054$, $B = -0.002$, $C_1 = 0.0003$, $C_2 = -0.0001$, $m = 0.67$, $\omega = 7.56$. The fitting window is bracketed by the two vertical dashed lines from August 2004 to December 2007 and lasts approximately 1200 days. The overall upward curvature in this log (price) versus time means the price accelerated faster than exponential, matching the LPPLS definition of a bubble (see text).

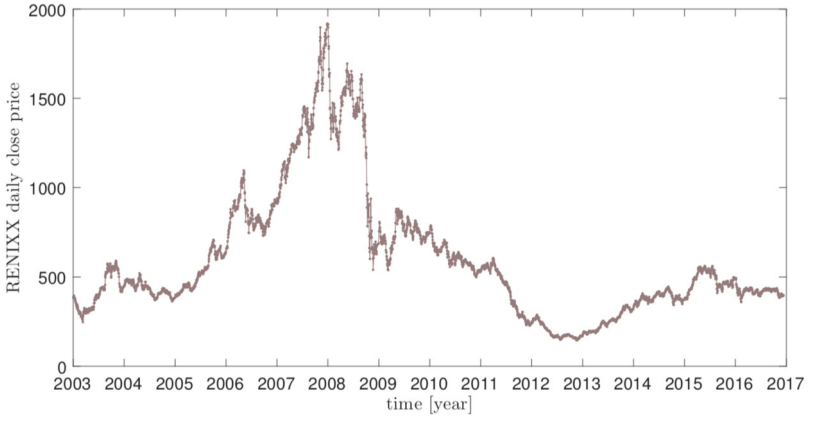

Figure 2. Renewable Energy Industrial Index (RENIXX) (daily close prices) as a function of time from January 2003 to December 2016.

estate bubble in the US and its stock market drawdown, associated with the 2008 Great Financial Crisis, the question arises whether the clean-tech bubble represented an intrinsic bubble in clean energy, or whether it was simply driven by the global market through a kind of contagion effect.

To disentangle the dynamics of the RENIXX index from that of the stock market, we can express the RENIXX 'in currency units' of the Standard & Poor's 500 (S&P500), a stock market index based on the market capitalisations of the 500 largest companies listed on the NYSE or NASDAQ, which is used as a global market indicator. In other words, we take the S&P500 index as the numeraire to express the value of the RENIXX index in relative terms as

$$\text{RENIXX-in-S\& P500}(t) = \frac{\text{RENIXX(t)}}{\text{S\& P500}(t)} \tag{2}$$

Figure 3 shows the ratio (2) in a logarithmic scale as a function of time. One can observe that this ratio increased by a factor of 4.3 (from 0.3 in December 2004 to 1.3 in January 2008) during the rise of the green-tech bubble. With the crash of the bubble, the ratio went down to 0.1 in November 2012, which represents a 12-fold decrease from the height of the bubble. Figure 3 demonstrates unambiguously that RENIXX massively over-performed the global US stock market for more than three years before underperforming it catastrophically for four years. In the aftermath of the Great Financial Crisis, the RENIXX index did not benefit from the quantitative easing programmes

Figure 3. RENIXX-in-S&P500(t) = RENIXX(t)/S&P500(t) daily close prices (in logarithmic scale) as a function of time from January 2003 to December 2016.

that were launched in the end of 2008 and developed for several years thereafter. This evolution of the 'RENIXX in S&P500' confirms that the RENIXX index went through an intrinsic bubble of its own, with a much larger amplitude than the US stock market at large. While we cannot exclude some contagion effects, the green bubble amplified extensively the exuberance of the pre-Great Financial Crisis regime.

3.4. The oil prize and the clean-tech bubble

As clean tech is considered to be a substitute for oil, and more generally for carbon-based energy sources, we now analyse in more detail how the oil price affected the clean-tech bubble. Before and during the clean-tech bubble, the oil price increased substantially before crashing (Sornette, Woodard, and Zhou (2009) for a detailed LPPLS study of the oil bubble). From 2004 to 2006, the oil price increased to exceed USD 75 a barrel in mid-2006 and then dropped back to USD 60 a barrel in early 2007. This decline in oil price has been attributed to slowing demand due to the global financial crisis, but Sornette, Woodard, and Zhou (2009) demonstrated also the presence of a significant speculative bubble component, which explained the abrupt change of regime and crash.

Figure 4 shows that the RENIXX index went through three main peaks before crashing. The first peak in December 2007 reflects the intrinsic endogenous dynamics of the clean-tech bubble, and its timing is accurately quantified by the LPPLS analysis, as presented in Figure 1 above. Within the LPPLS framework, this peak and its subsequent crash reflect the psychology of investors who realised that—given that renewable and clean energy is more complex and costly to develop than expected—the super-exponential exuberant pricing was neither justified nor sustainable. However, as the oil price was still accelerating, and analysts were extrapolating that the oil price could reach USD 200 or more within the next two years (Menon 2008), investors were enticed to re-adjust their valuations of clean-tech upward, leading to a short rebound of the RENIXX index after its first crash of 35%. This rebound paralleled for a while the growth of the oil price, however with a first drop after the second peak before the oil price peak, followed by a rebound (third peak). This shows the strong susceptibility of the RENIXX index over this time period, as revealed by the LPPLS analysis that identified the change of regime as the expected development following its bubble phase. Figure 4 shows an apparent synchronisation of oil and RENIXX in their big crashes (see Figure 5 for a more detailed view).

The relation between the two-time series during the crash following the second peak is very informative about the influence of the oil price on the RENIXX. The period of the crash is magnified in Figure 5, which suggests that both time series are closely related. This visual impression is

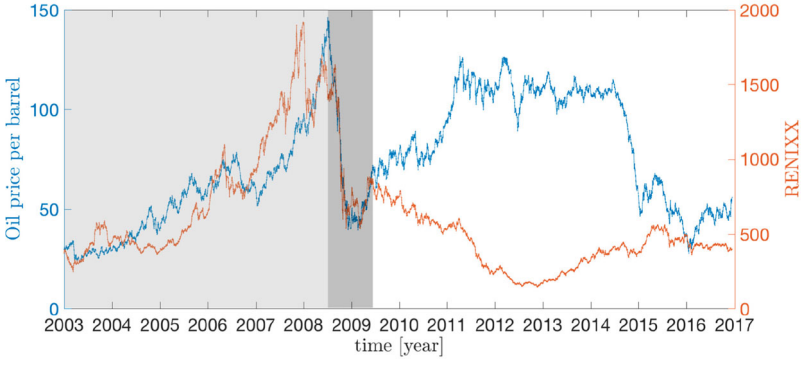

Figure 4. The oil price per barrel in blue, on the left scale, and Renewable Energy Industrial Index (RENIXX) in red, on the right scale, (both daily close prices) as a function of time from January 2003 to December 2016.

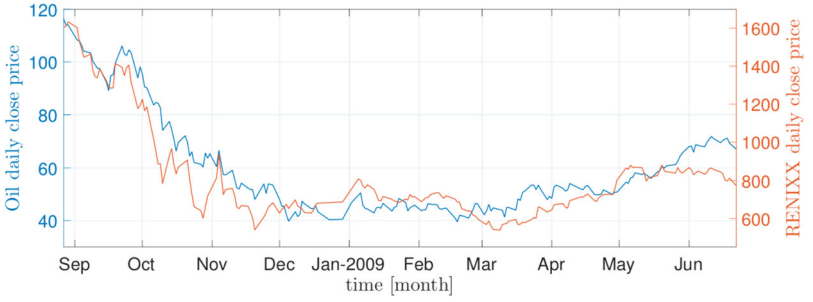

Figure 5. The oil price per barrel on the left scale in blue, and Renewable Energy Industrial Index (RENIXX) on the right scale in red, (both daily close prices) as a function of time from 27 August 2008 to 22 June 2009.

confirmed formally by implementing the Johansen test for cointegration (Johansen 1995) on the RENIXX index and the oil price. The cointegrated VAR model is given by

$$\Delta y_t = A(B' y_{t-1} + c_0) + c_1 + \varepsilon(t), \tag{3}$$

where y_t is the vector composed of the two variables (RENIXX, oil price) at time t, A is the adjustment speed, B' is the cointegrating vector, c_0 and c_1 are two constants and $e(t)$ is the noise residual. On the sample of 195 daily prices from 27 August 2008 to 22 June 2009 shown in Figure 5, the null hypothesis of no cointegration is rejected at the 99% confidence level (p-value = .01). The clear cointegration of the drawdowns of the two times series supports the hypothesis that the second peak in the RENIXX was caused by the very high oil price. And the second drawdown of the RENIXX index, delayed by the strong oil price upsurge, seems to be freed to express its full power with the crash of the oil price.

In order to further disentangle the dynamics of the RENIXX index from that of the oil price, we express the RENIXX 'in currency units' of the oil price, as shown in equation (4), in the spirit of the previous equation (2),

$$\text{RENIXX-in-oil}(t) = \frac{\text{RENIXX}(t)}{\text{oil price}(t)} \tag{4}$$

The grey rectangle in Figure 6 outlines the period from 2003 to 2009 during which the ratio (RENIXX/oil price) remained in a band between 8 and 20. During this period, RENNIXX/oil price increased from

Figure 6. RENIXX-in-oil(t) defined by equation (4) (in logarithmic scale) on the left scale in blue, and Renewable Energy Industrial Index (RENIXX), on the right scale in red (both daily close prices), as a function of time from January 2003 to December 2016. The grey rectangle highlights the period from 2003 to 2009 when the RENIXX was intertwined with the oil price. The pink band highlights the period from 2009 to 2012 when the RENIXX decoupled from the oil price and the ratio RENIXX/oil price declined nearly continuously in a kind of death spiral for the RENIXX.

8 in early 2005 to 20 towards the end of 2007, confirming the specific bubble nature of the clean-tech sector. While oil prices had a clear influence, the RENNIXX developed a life of its own with a 2.5-fold appreciation compared with oil prices. While the market accounted somewhat for the substitutional value of alternative energy sources when the oil price surged, the clean-tech sector develops its specific dynamics. In 2009, the RENIXX decoupled from the oil price when the oil price per barrel reached over USD 100 and the RENIXX started a continuous decline (Alsayegh 2016). This period is indicated within the pink band in Figure 6. The ratio RENIXX/oil price went from 20 in December 2007 to 1 by the end of 2012. This massive decoupling between renewable energy and the oil price most likely resulted from investors recalibrating their expectations for clean energy in the aftermath of the burst of the clean-tech bubble and in view of the apparent broken promise of never-ending increasing oil prices.

In the next section, we will now analyse the social dynamics underlying the clean-tech bubble in more detail.

4. 'Salvation and profits': the clean-tech bubble as a social bubble

4.1. Main elements of a social bubble

In the history of technology and financial markets, bubbles have often accelerated the development, diffusion and adoption of many transformative technological innovations. Financial and social bubble share a universal pattern: they result from strong social interactions between enthusiastic supporters of a technological, scientific, political, or entrepreneurial project or idea (Sornette 2008). Exceptional enthusiasm leads to imitation and herding behaviour, which, in turn, creates positive feedback loops, where recent price appreciations and positive developments further justify future endorsement of the hyper-optimistic narrative supporting the bubble. In such a social bubble, we can identify the following phases:

- Initial scientific or technological breakthrough, specific idea, invention, or project;
- Public and private investments, which result in increasing price or valuation growth in corresponding firms, sector, or market; this growth attracts other less sophisticated and international investors that further fuel price increases;
- Proliferation of ventures of all kinds (which often leads to the dismissal of best-practice models, such as standard risk-benefit analyses, which, in turn, reduces collective risk-aversion), leading to unsustainable accelerated price increase;
- Disappointing outcomes, reassessment and hard confrontation with reality, abrupt project or programme termination.

If we now map these generic features onto the clean-tech bubble, it becomes evident that this bubble shared many of the ingredients of a social bubble. We will now explore in more detail the social dynamics that have fuelled the clean-tech bubble.

4.2. The narrative economics of the clean-tech bubble

Historically, at the core of each bubble, we can identify a narrative that resulted in speculative contagions and bubble dynamics. While narratives are key factors in the emergence of bubbles, a comprehensive analysis of bubble narratives has been lacking. Economist Robert Shiller advanced only recently what he calls narrative economics, which is the study of the 'spread and dynamics of popular narratives […] to understand economic fluctuations' (Shiller 2017, 2020).

The clean-tech bubble is one of the purest examples of a bubble that has been driven by a narrative. The core narrative of the clean-tech bubble is encapsulated in 'salvation and profits', the title of the talk venture investor John Doerr gave on clean tech. While clean tech represented an

opportunity to be exploited for profit—an opportunity 'bigger than the Internet'—it also had a quasi-religious dimension: investing in clean tech could promise 'salvation'. As Shiller notes, a narrative that has emotional resonance has a potential for contagion. Doerr, for example, started his talk with an anecdote that, during the talk, moved him to tears. The clean-tech narrative invariably involves a reference to 'crisis' and 'catastrophe'. The impending climate crisis creates an immediate personal and emotion-lading connection to the narrative that fuels the contagion of the narrative at the core of the speculative bubble (Shiller 2017).

Similarly, Elon Musk, a co-founder of electric vehicle-maker Tesla, constantly mobilises references to climate change and an impending catastrophe when he refers to the mission of his company. In a blog post on Tesla's website, Musk writes, activating the emotional connection to the narrative: 'We must achieve a sustainable energy economy or we will run out of fossil fuels to burn and civilization will collapse' (Musk 2016). Tesla is, therefore, according to Musk 'very important for the future of the world […]. If we do not solve the environment, we're all damned' (Musk 2018). We can identify in Musk's rhetoric 'salvation' and 'damnation' as important imagery, which also Doerr employed, and that is inexorably linked with narrative driving the clean-tech bubble, in particular, and clean-tech in general.

Historically, energy and narratives have been deeply intertwined. As the example of nuclear energy illustrates, narratives about technologies, its promises and perils, fundamentally shape their trajectories (Weart 2012). The rise of nuclear fear demonstrates how powerful collectively-shared narratives and imagery is for technological adoption and diffusion. The narratives of alternative 'clean' or 'renewable' technologies of energy, which followed the anti-nuclear narratives of 'contamination' and 'doom', also powered the clean-tech bubble. 'Clean' and 'renewable' give rise to a spiritual, quasi-religious, or mystical imagery of purification, healing and renewal, which contrasts with the deeply entrenched and collectively-shared imagery of crisis and pollution that nuclear energy and fossil fuels invoke.

In the following section, we will examine why the clean-tech bubble went bust. We will then address the question whether the clean-tech bubble resulted—similar to preceding innovation-accelerating bubbles—in novel technological breakthroughs and a large-scale adoption of clean technologies.

4.3. The clean-tech bubble as a social bubble

At the core of previous social bubbles was often a specific technological breakthrough. In contrast, the speculative enthusiasm to invest in clean technologies was largely driven by the hyped threat of climate change, which was reasoned to be the harbinger of fundamental societal shifts.

After the collapse of the dot-com bubble in the early 2000s, venture capitalists started to identify what Schumpeter termed 'new economic spaces' (Schumpeter 1939). For these investors, clean or renewable energy represented such a new economic space in its early stages with new and potentially high-growth industries. Private and public clean-tech investments triggered a positive feedback loop, which attracted new capital, entrepreneurs and startups. Fuelled by federal subsidies and tax credits, new clean-tech ventures proliferated. Coupled with the herding and imitation behaviour of Silicon Valley venture capitalists, in particular resulting from the so-called 'fear-of-missing-out', government funding of the emerging clean-tech sector reduced risk-aversion and distorted market signals. While it seemed that clean or renewable energy represented a high-growth sector, the market was mainly growing because of a massive inflow of venture capital and government subsidies. The VC-model—which relies on scalability, rapidly growing markets and exit opportunities—failed in hardware-dominated clean technologies because of the capital intensity and the long time horizons required for commercialising and scaling these emerging technologies.

The enthusiasm for clean-tech turned out to be inflated. Investors and entrepreneurs in the early phase of the bubble developed extraordinarily over-optimistic expectations about the total addressable market and the future large-scale adoption of clean or renewable technologies. While it was in

most cases unclear how these novel technologies could be produced, commercialised, scaled and diffused, very large amounts of capital were nevertheless flowing into clean technologies and start-ups. Similarly, investors and entrepreneurs had unrealistic expectations about the size of the total addressable market—they were indefinitely optimistic about the transformative potential of clean-tech technologies and size of the market they can capture (Thiel and Masters 2014). Driven by hype, imitation behaviour among investors and entrepreneurs, and massive government subsidies, which reduced collective risk aversion and distorted market signals, investors and entrepreneurs took inordinate risks that would not otherwise be justified by standard due diligence processes, cost–benefit and portfolio analyses. As a consequence, investors' unrealistic expectations about the future of clean technology crashed and VC investments in the sector decreased from USD 4.1 billion in 2008 to USD 2.5 billion in 2009.

The clean-tech bubble was clearly a social bubble: the narrative of a 'moral imperative' to combat climate change and achieve 'salvation', the ballooning venture capital investments, and the massive government subsidies weaved a network of self-reinforcing spirals that led to over-optimistic expectations, excessive enthusiasm and over-investments. The question now arises whether the clean-tech bubble has—as it has been historically the case for a number bubbles (but not all)—accelerated the development, deployment and diffusion of clean technologies.

5. Conclusion: seeing green?

Although the clean-tech bubble went bust, we can identify some factors that indicate that the bubble did indeed catalyse technological progress in clean and renewable energy technologies. The global capacity of solar photovoltaic, for example, increased from 6 installed gigawatts in 2006 to 303 installed gigawatts in 2016 globally, which represents an increase by a factor of 50 over 10 years. Furthermore, the additional installed capacity has been—except for 2011—increasing every year since 2006. Global wind power capacity progressed by a factor of 6.5 from 2006 to 2016, increasing from 74 to 487 installed gigawatts. By the end of 2016, more than 90 countries had been actively involved in commercial activities surrounding wind power, and at least 24 countries met 5% or more of their annual electricity demand with it. And the global capacity from combined solar photovoltaic and wind power increased by a factor of 10 between 2006 and 2016.

Over the last decade, costs for renewable and clean energy technologies also started to significantly decrease. In other words, similar to the exponential increase in computing power that is referred to as Moore's Law, solar technology experienced, in the decade that followed the clean-tech bubble bust, an exponential decrease in costs. This exponentially decreasing cost curve—or increasing learning curve—is captured by Wright's Law, which models an exponential decline in the cost of technologies as a function of the cumulative scale of production.[1] In the case of solar, it is well-established that the price of solar modules per watt of power drops by around 25% for every doubling of cumulative manufacturing. Even when accounting for the costs of overall solar systems, which include mounting systems, tracking systems, DC-to-AC inverters, cabling, etc., the cost of the overall solar technology follows an exponentially decreasing curve (Naam 2020). Lithium-ion batteries, which are an integral part of electric vehicles, also experienced a similar drop in prices (Lee 2020).

Another startup and industry that emerged successfully from the bust of the clean-tech bubbles are Tesla and electric vehicles, respectively. By starting with a very small submarket—the market for electrically powered sports cars—then expanding into other submarkets with cheaper models and, ultimately, into a vertically-integrated clean energy business, Tesla validated clean tech and climate change as viable investment categories. Furthermore, Elon Musk demonstrated that Silicon Valley is capable of building large-scale and capital-intensive businesses, such as car companies. In other words, after the bursting of the bubble, Musk and Tesla became symbols for clean tech and a model that could be imitated by other entrepreneurs and investors. And indeed, funding for battery and electric vehicles startup has started to accelerate in this decade—to the extent that

there are mounting concerns about another clean-tech bubble in the making. However, this time, the dominant narrative is less about 'clean tech' but more about 'sustainability', 'climate tech' and 'ESG'. Whereas investors invested around USD 16 billion in 2015, investors allocated more than USD 36 billion to climate-related technology in 2019. For comparison, in the aftermath of the clean-tech bubble, clean or climate tech attracted USD 418 million from VCs, which represents three times the growth rate of venture investments into artificial intelligence. Many new private equity and VC funds, foundations, and family offices that invest only in clean technologies have been launched over the past few years. Breakthrough Energy Ventures, founded in 2015, for example, is a USD 1 billion vehicle that invests only in startups with the potential to cut annual greenhouse-gas emissions by at least the equivalent of half a gigaton of CO2—some 1% of the world's total. Other funds provide new financing models that finance capital-intense clean-tech and climate startups so that they can escape the 'valley of death'.

There are a few factors that differentiate clean-tech investments in this decade from the bubble that formed in 2004. For example, lower yields force investors into long-duration assets, such as green infrastructure, which, due to ESG, have become more attractive than oil & gas. The rise of 'patient' or 'impact' capital also extended time horizons for capital and time-intense clean energy investments. In contrast to the last clean-tech bubble, which was fuelled by venture capital investors and government funding, larger investors, such as private equity firms or corporations, are now investing in capital-intensive clean technologies, such as solar and wind, or carbon capture technologies. VCs, in turn, started to invest more in differentiated and lower-cost sectors, such as solar services and financing, lab-grown meat, climate-related software, or electric vehicles. Whereas there was a lack of acquisitions by large companies in 2008—which, as we have noted above, reduced exit opportunities for investors—the recent SPAC wave fuelled a series of clean-tech exits and acquisitions. More than two dozens clean-tech startups gone public through SPACs, that is, special purpose acquisition companies that acquire and take company public in reverse mergers. Moreover, large tech companies, such as Google, Apple, Microsoft, or Amazon, have started to invest in transforming their energy systems and infrastructures, such as data centres, telecom networks and devices, which, in turn, has accelerated the market for clean and renewable energy.

In essence, the clean-tech bubble of the mid-2000s catalysed a massive decrease in cost by excessively funding research and development in different clean-tech sectors, such as solar or wind. While almost all of the clean-tech startups of the last bubble failed, the clean-tech bubble, by decreasing prices and funding innovation, massively de-risked clean and renewable energy technologies. Solyndra, for example, failed because it was trying to market a cutting-edge new solar cell, which ended up being too expensive when the design costs started to decrease. Today, solar or wind are no longer risky technologies and are now even cost-competitive with legacy energy sources, such as gas or coal. This decrease in costs and the elimination of technical risks of clean tech is now catalysing more investment opportunities, which, in turn, attracts new entrepreneurs and investors.

One of the most important properties of financial bubbles is their resemblance with self-fulfilling prophecies. For example, Tesla, which emerged from the bust of the first clean-tech bubble, is realising its vision of 'accelerating the world's transition to sustainable energy'. The firm single-handedly created markets for electric vehicles and batteries. Over 250 firms are now manufacturing electric vehicles and large legacy car makers are expected to invest up to USD 500 million into electric vehicles over the next five years. While the bursting of the clean-tech bubble in 2009 unquestionably resulted in massive losses for investors—an estimated USD 12 billion were lost (Weyant, Fu, and Bowerscok 2018)—novel technological breakthroughs, massively cost-reduced wind and solar technologies, and new industries between, for example, solar and electric-vehicle manufactures and battery producers, have been emerging from its debris. If the problem of climate change and abundant energy needs to get solved, it almost seems that we might need another clean-tech bubble – one that avoids the failures of the first bubble that burst in 2009.

Note

1. According to Nagy et al. (2013), this exponential cost curve decrease can be detected in at least 60 other technologies.

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